Introduction to Image Processing

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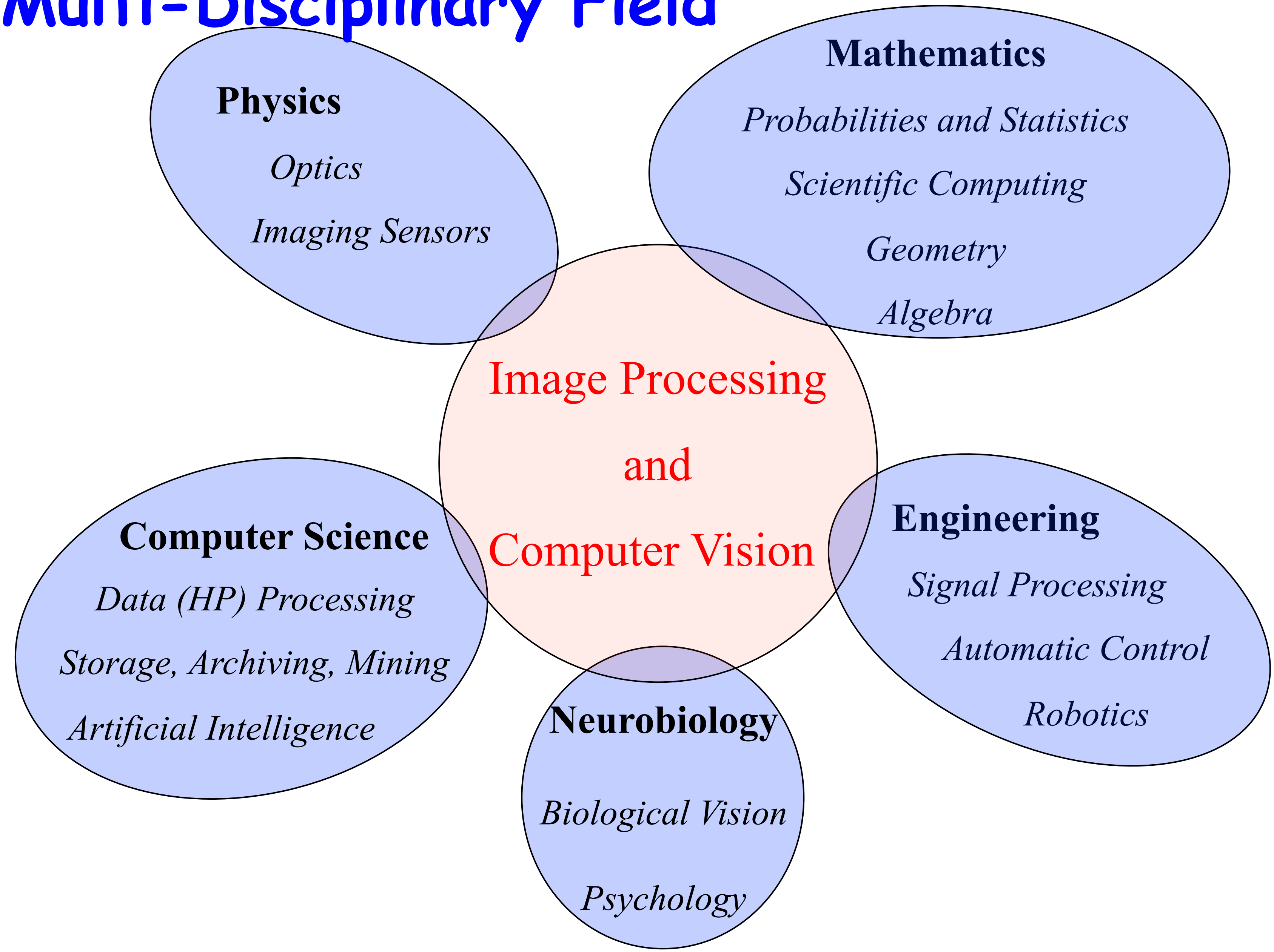
What is "Image Processing"?

- *(Definition from Wikipedia)* "**Image Processing** is any form of information processing for which the input is an image, such as photographs or frames of video; the output of image processing can be either an image or a set of characteristics or parameters related to the image. Most image-processing techniques involve treating the image as a two-dimensional signal and applying standard signal processing techniques to it."

Applications of Image Processing

- Medical Applications (e.g., Cancer Detection, Remote and Assisted Surgery)
- Security Applications (e.g., Face and Fingerprints Recognition)
- Commercial Applications (e.g., Video and Photograph Enhancement)
- Industrial Applications (e.g., Assembly Line Manipulation,Visual Inspection)
- Military Applications (e.g., Missile Guidance)
- Space Applications (e.g., Remote Sensing, Space Robotics)

Multi-Disciplinary Field



Sequence of Image Processing Tasks

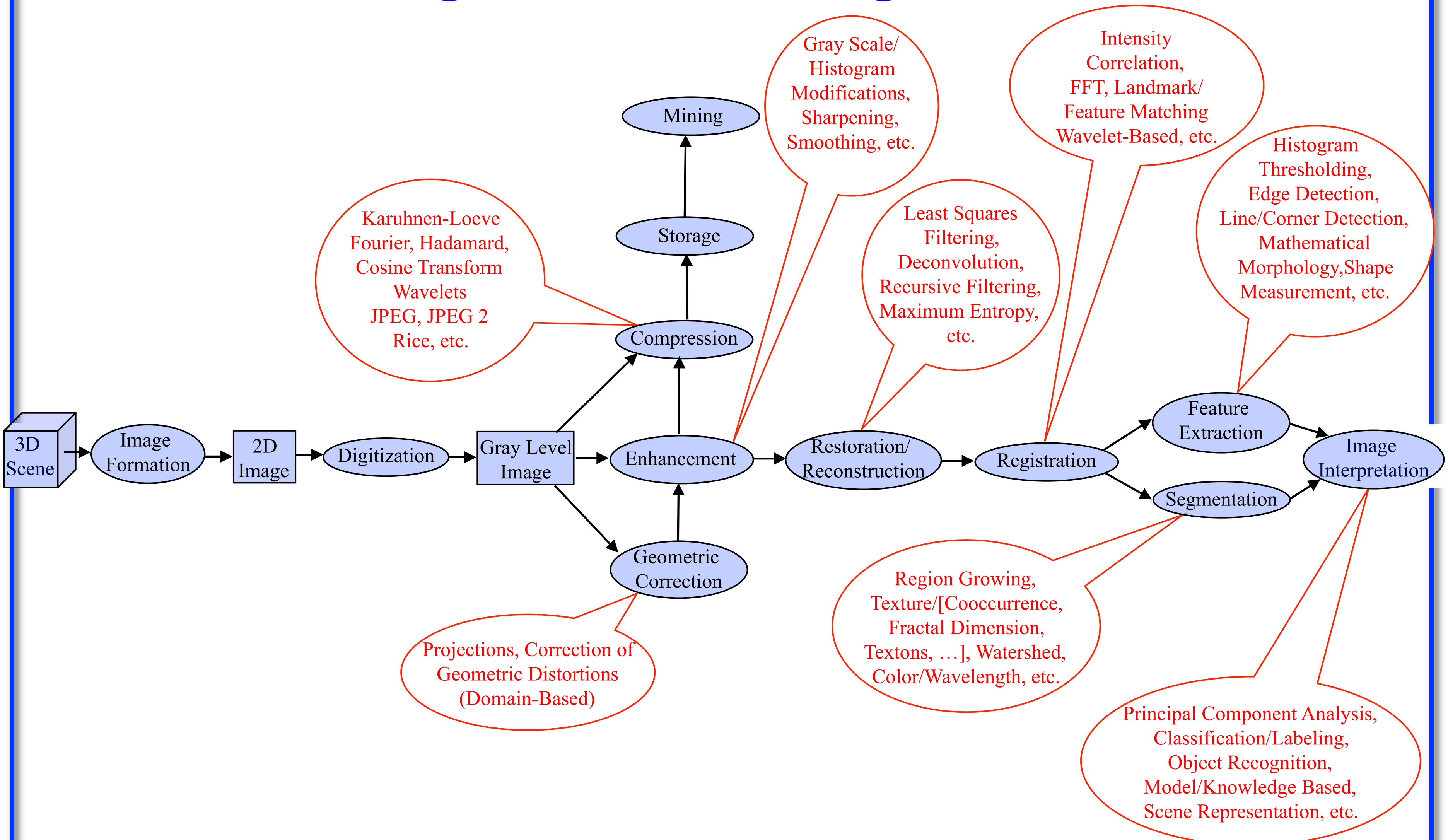
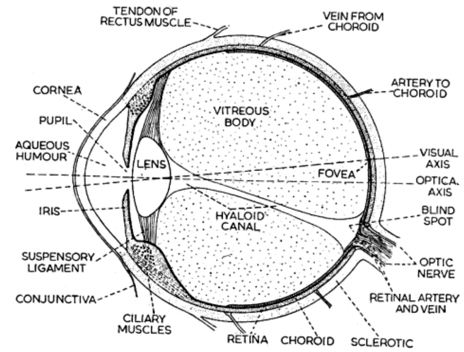


Image Formation

Biological Vision



- Visual functions Integrated by Brain:
  - Field of View, Focusing Ability, Depth Perception, Motion Perception, Color Perception

- Different Kinds of Vision/ "See" and "Understand" in Different Ways
  - Human Vision
    - Image Formed on the Retina/ photoreceptors (or rods and cones), produce electrical transmitted to brain via optic nerve.
    - 3 kinds of color receptors - blue, greenwish-yellow and red
    - Position of eyes determines degree of peripheral vision; Visual field of 200º; Stereo vision => depth
  - Animal Vision:
    - Dogs:
      - 2 kinds of color receptors - yellow and greenish-blue
      - Visual field of 240º but central binocular field of view ≈1/2 human's
      - Optimal dilation of pupil (≈ camera's aperture) + reflective layer under retina => Enhanced night vision
      - Lower details sensing (no fovea); Greater sensitivity to motion
    - Snakes:
      - Do not see color
      - Combination of light receptors: rods => low-light fuzzy vision & cones => clear images
      - Underground snakes: smaller eyes/light and dark; above ground: very clear vision and good depth perception. Some species (e.g., boas and pythons): pit organs similar to IR goggles.
    - Insects:
      - "Compound eyes: Bees' eyes made up of 1000's of lenses, dragon flies 30,000's
      - Wide field of view, and better motion perception

Biological Vision

- Optical Illusions, Illumination, A-priori Knowledge, Domain-Dependent

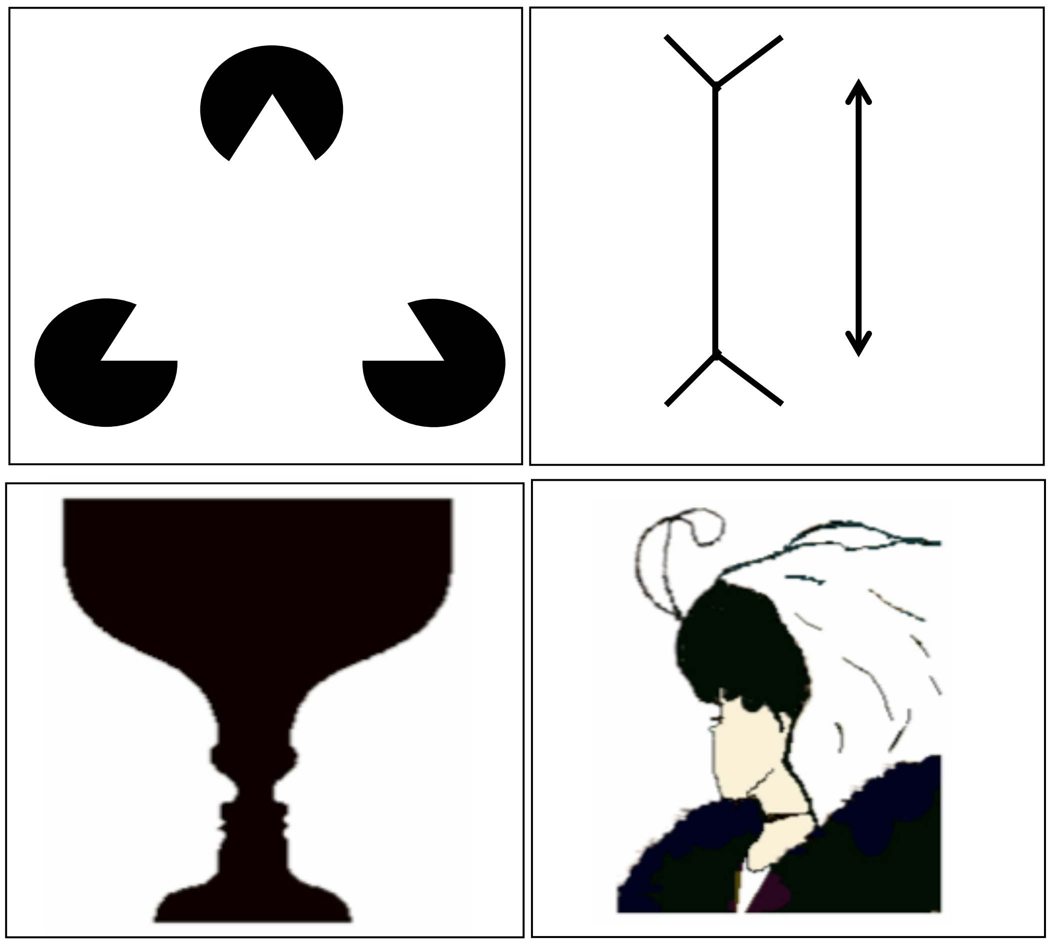
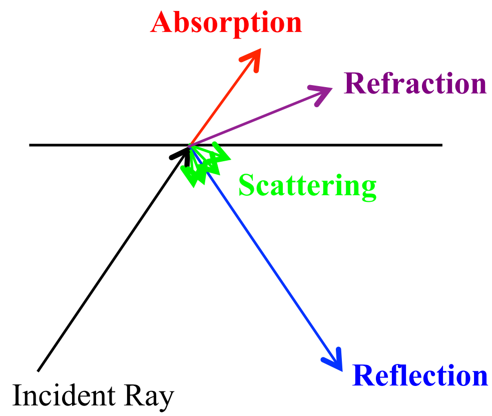
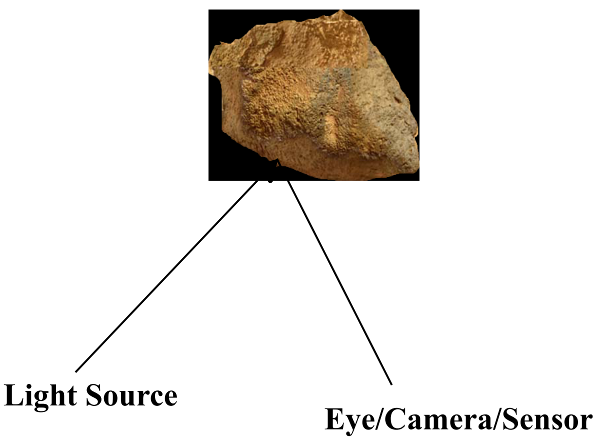


Image Formation - Physics

- Vision uses Light Reflected from the Surrounding World to Form an Image





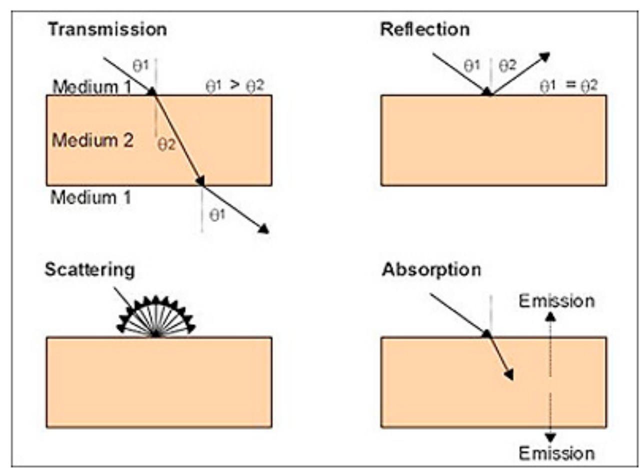
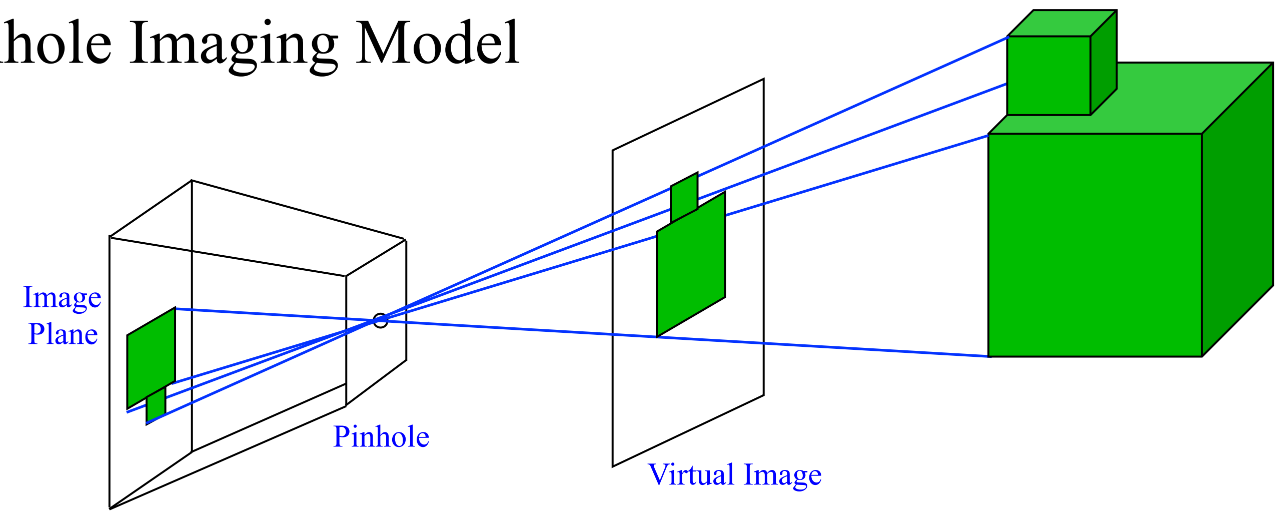
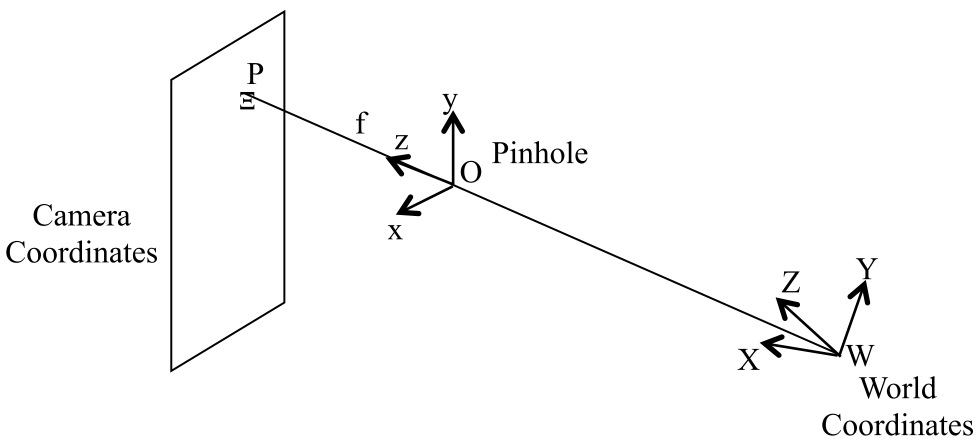


Image Formation - Optics

- Pinhole Imaging Model



- Perspective Geometry



If W = (X,Y,Z) and P = (x,y,f)

$\vec{OW} = \alpha . \vec{OP}$ so $\begin{cases} X = \alpha\, x \\ Y = \alpha\, y \\ Z = \alpha\, f \end{cases}$

Therefore

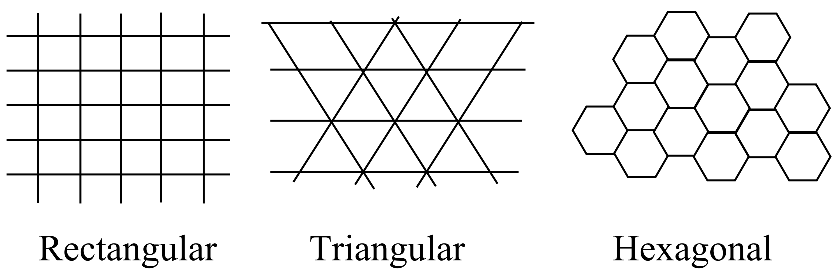
$$\begin{cases} x = f \,.\, X/Z \\ y = f \,.\, Y/Z \end{cases}$$

(with f is the focal length of the camera)

Digital Images

- Mathematical Model: Representation of an Image as a Discrete (Intensity) Function of Spatial Samples
  - I: (x,y) -----> I(x,y) = Gray Level at Pixel (x,y)
  - Gray Levels = Discrete Values Taken by Intensity Function

- Pixel ("Picture Element") = Image Representation of a Basic Volume Element in the World
  - Tesselation: Pixel Organization

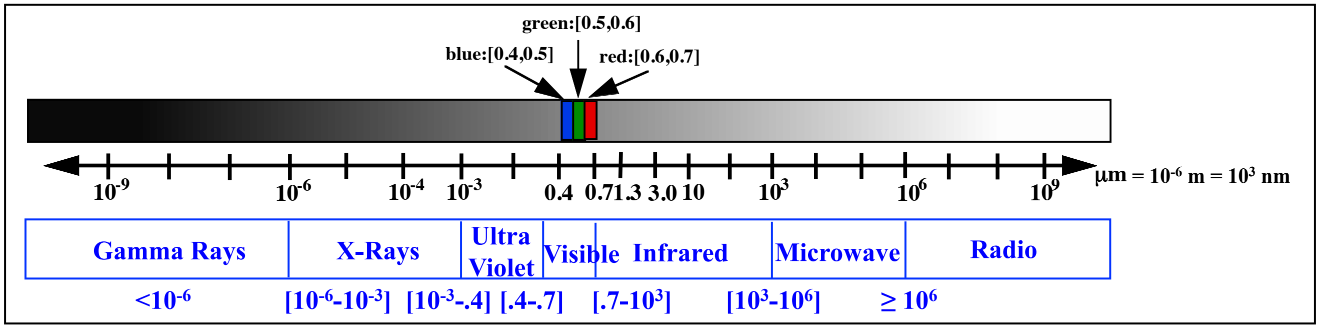


- Spatial Resolution = Represents Interval Sampling of 2D/3D Space

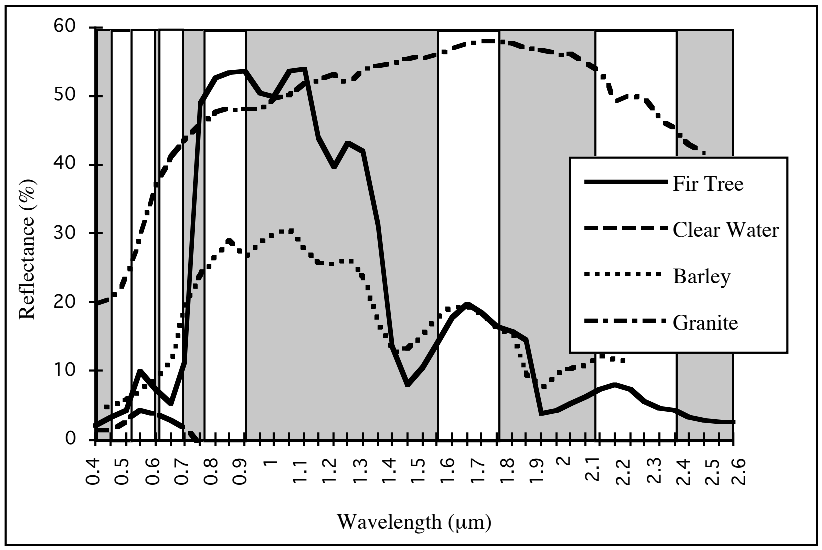
- Spectral Resolution = Represents Interval Sampling of Electromagnetic Spectrum

- Radiometric Resolution = Refers to the Number of Digital (Gray) Levels Used to Represent the Data

Remote Sensing Imaging



Electromagnetic Spectrum



Examples of Spectral Response Patterns for 4 Different Types of Features - Fir Tree, Clear Water, Barley, Granite - White Areas Show the Portions of the Spectrum Corresponding to the 7 Channels of Landsat-Thematic Mapper (TM)

Signal to Noise at Wavelength λ :

$$(S / N)_\lambda = D_\lambda \beta^2 (H/V)^{1/2} \Delta_\lambda L_\lambda$$

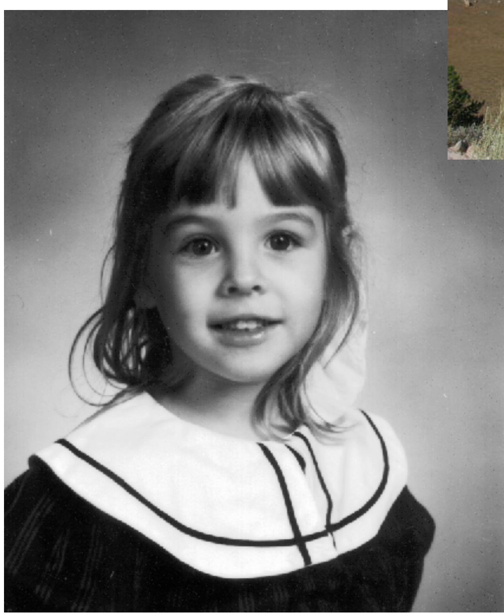
Where

- D_λ : detectivity (measures detector performance quality)
- β : instantaneous field of view
- H : flying height of the spacecraft
- V : velocity of the spacecraft
- Δ_λ : spectral bandwidth of the channel (spectral resolution)
- L_λ : spectral radiance of ground feature

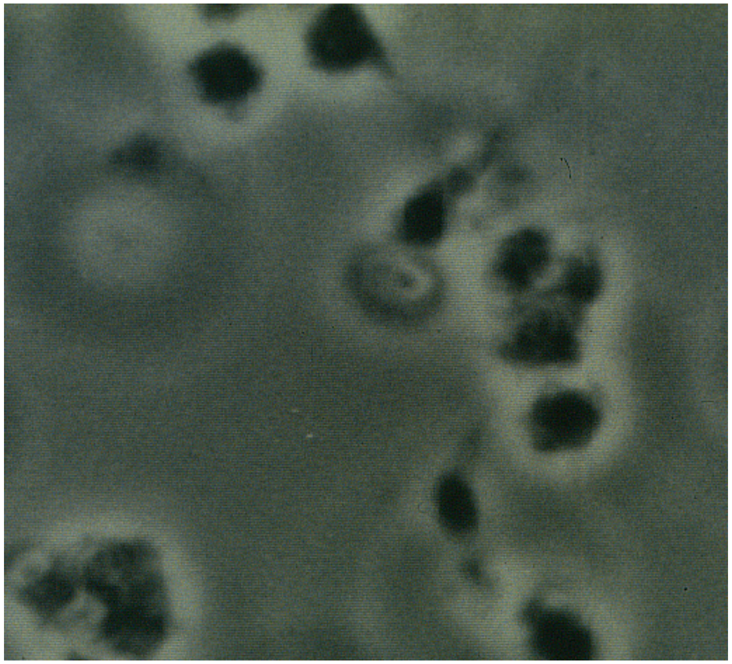
=> *<u>Tradeoff between spatial and spectral resolutions,</u> e.g.:*
To maintain the same SNR while improving spatial resolution by a factor of 4 (i.e., decreasing β by a factor of 2), we must degrade the spectral resolution by a factor of 4 (i.e., increase Δ_l by a factor of 4)

Remote Sensing Imaging (2)

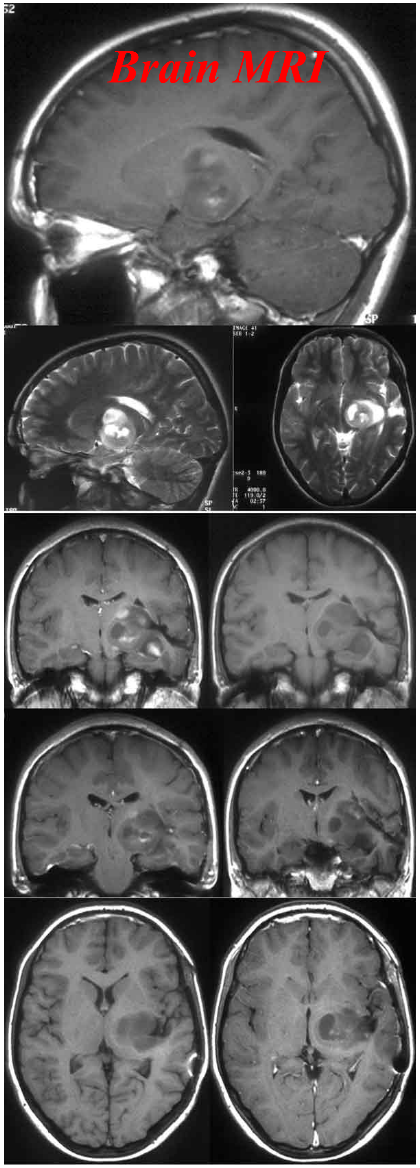
Imaging Examples - Photographs



Imaging Examples - Medical

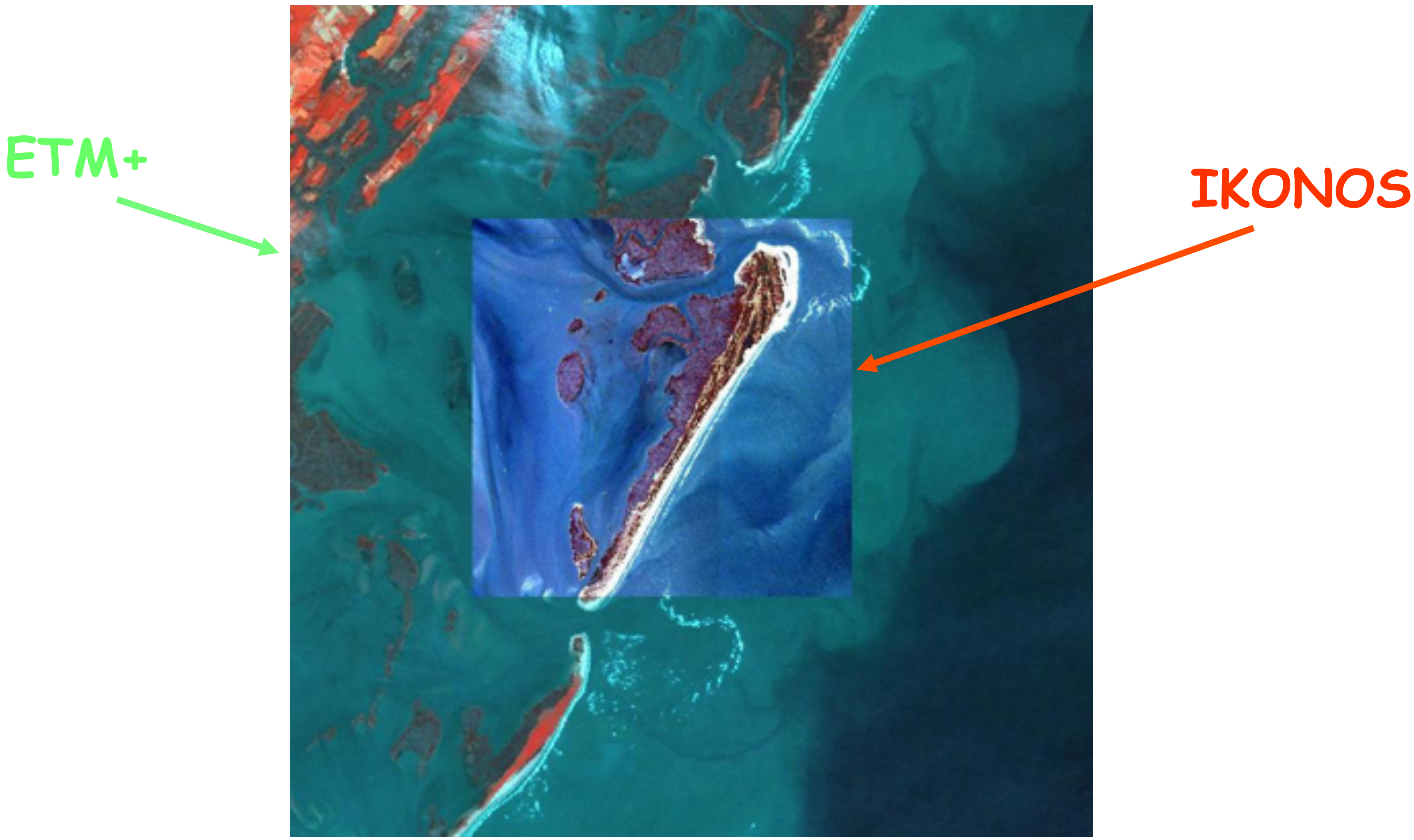


Blood Platelets



Earth Science Imaging

ETM/IKONOS Mosaic of Coastal VA Data



Hubble Space Telescope Imaging

(Barred Spiral Galaxy NGC1672)

Planetary Imaging

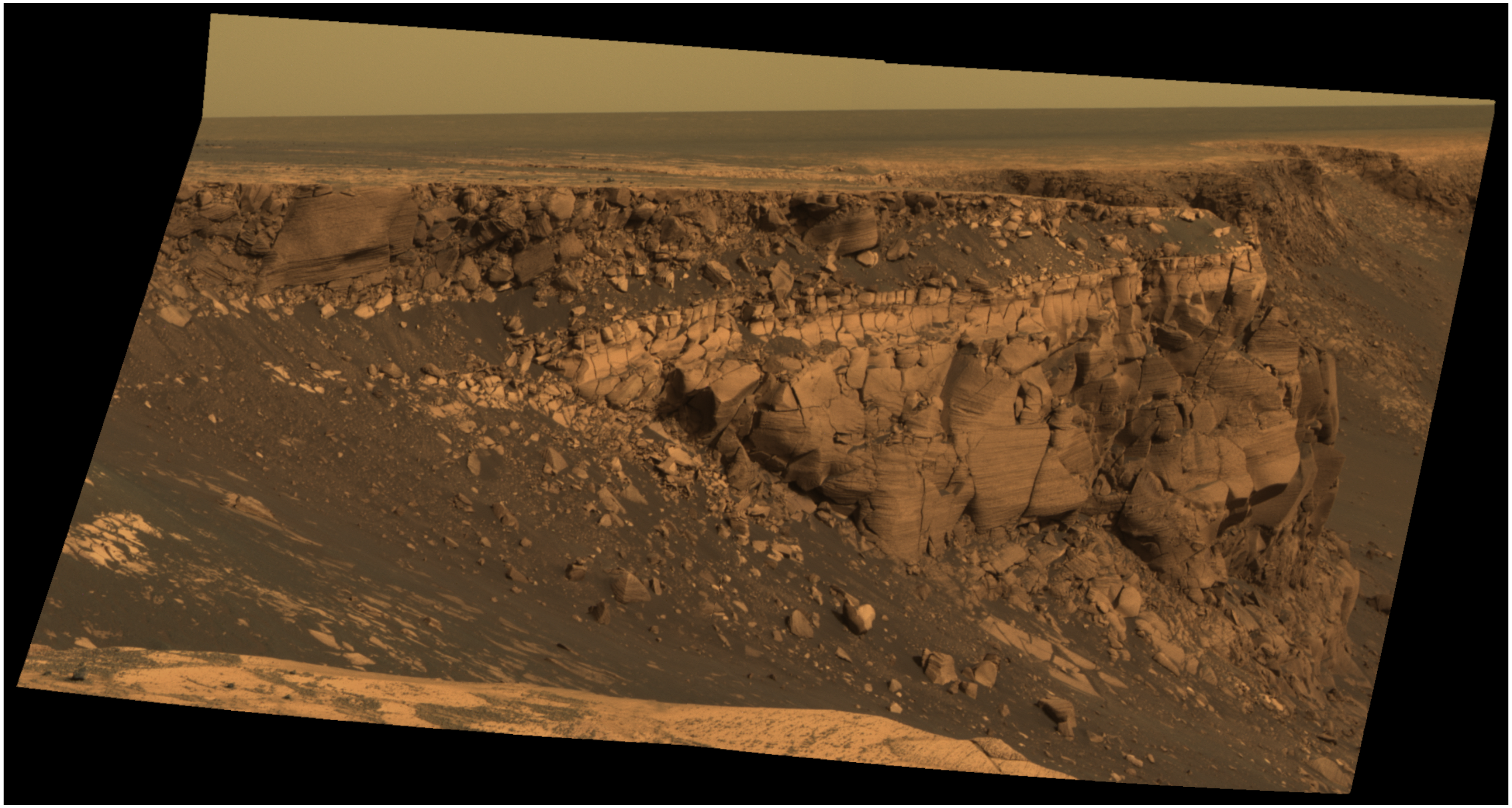
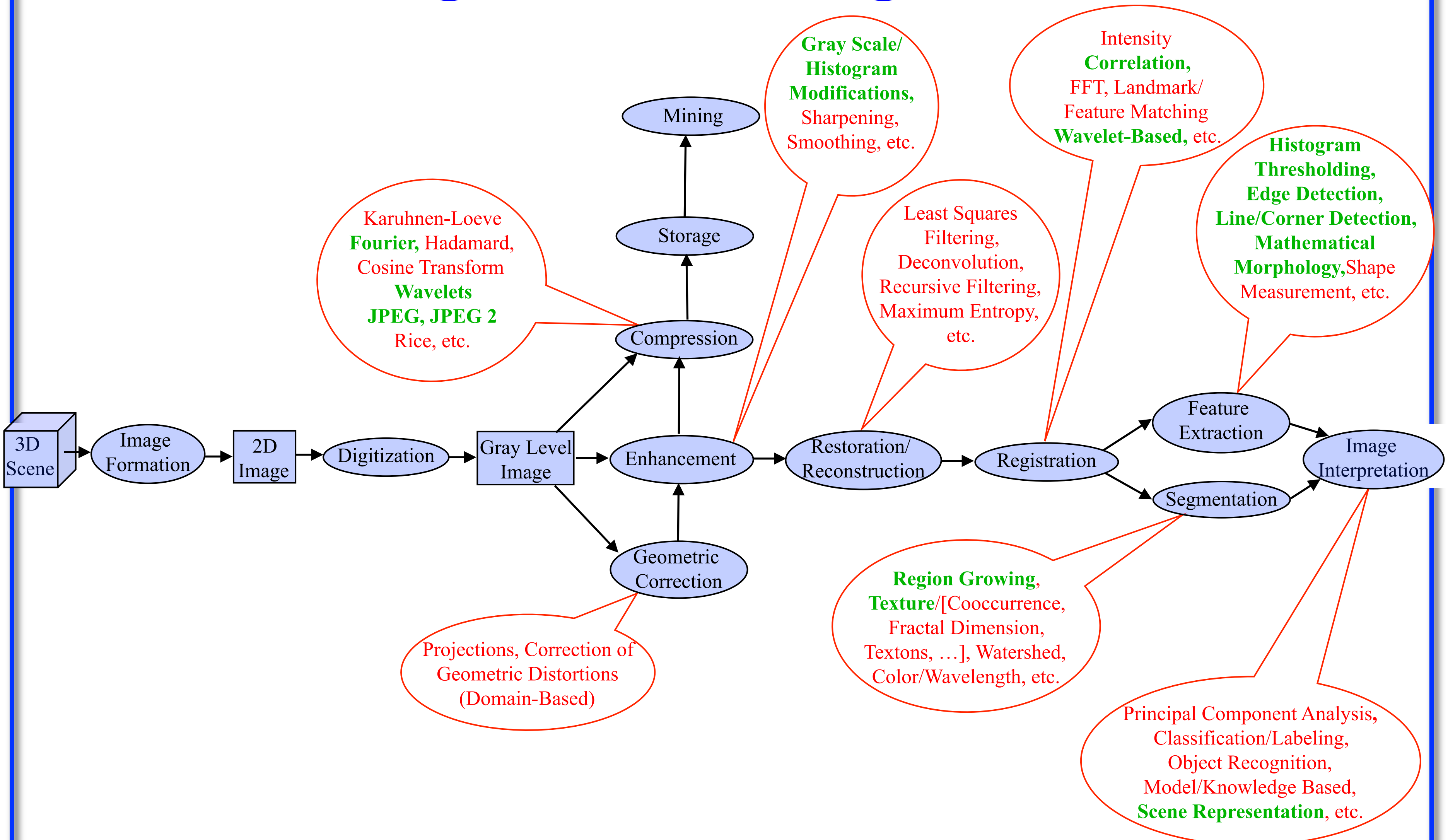


Image Processing Steps

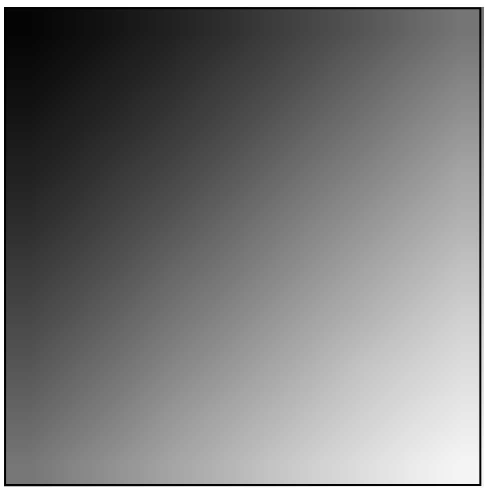
Sequence of Image Processing Tasks



What is Image Processing ?

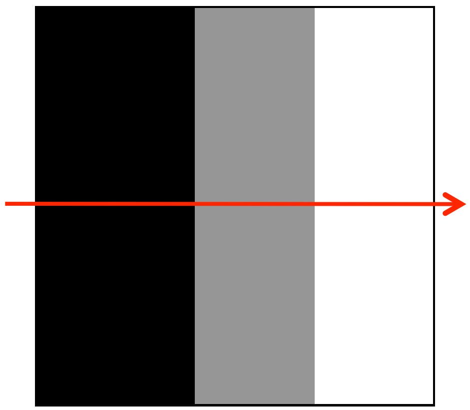
Test Case:

- 10 by 10 pixels Image
- 256 gray levels
- Image = 10 x 10 Matrix Made up of Numbers in Range [0-255]

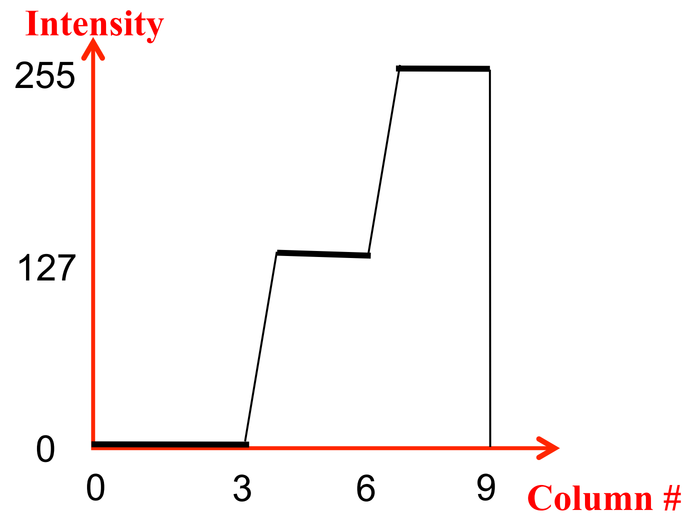


0					64				127
				64				127	
			64				127		
		64				127			
	64				127				
64				127					191
			127					191	
		127					191		
	127					191			
127					191				255

Image Processing Basics



Intensity Function :



0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255

Gray Level Histogram :

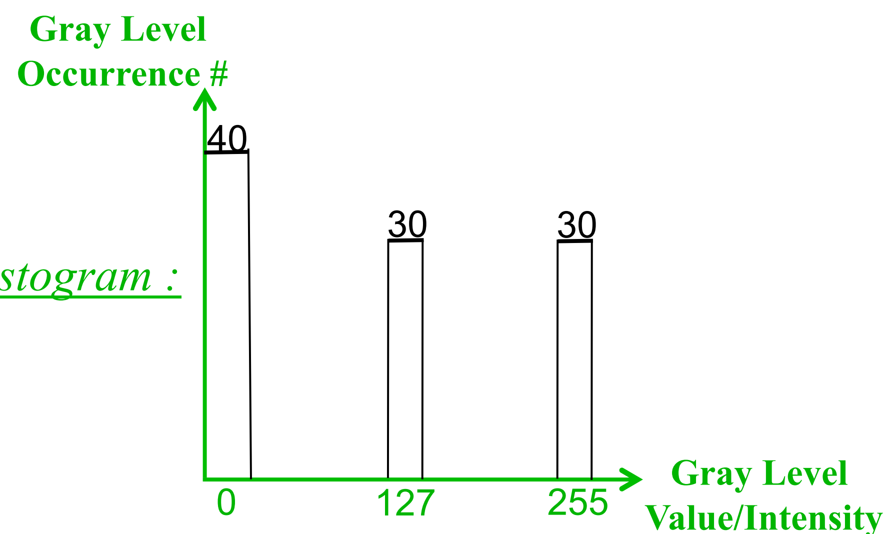


Image Convolution

- Many Image Processing Operations are "Local"
  - o Smoothing, Edge Detection, Slope Computation, Wavelet Transforms, etc.
  - o Parallel Computations

- Pixel Neighborhood, N

	1	
2	Center Pixel	4
	3	

4 Neighbors

1	2	3
8	Center Pixel	4
7	6	5

8 Neighbors

3 Ξ 3 Neighborhood

1	2	3	4	5
6	7	8	9	10
11	12	Center Pixel	13	14
15	16	17	18	19
20	21	22	23	24

5 Ξ 5 Neighborhood

- Image Convolution
  - – Convolution of Image I with Filter h at Pixel (x,y) is defined by:

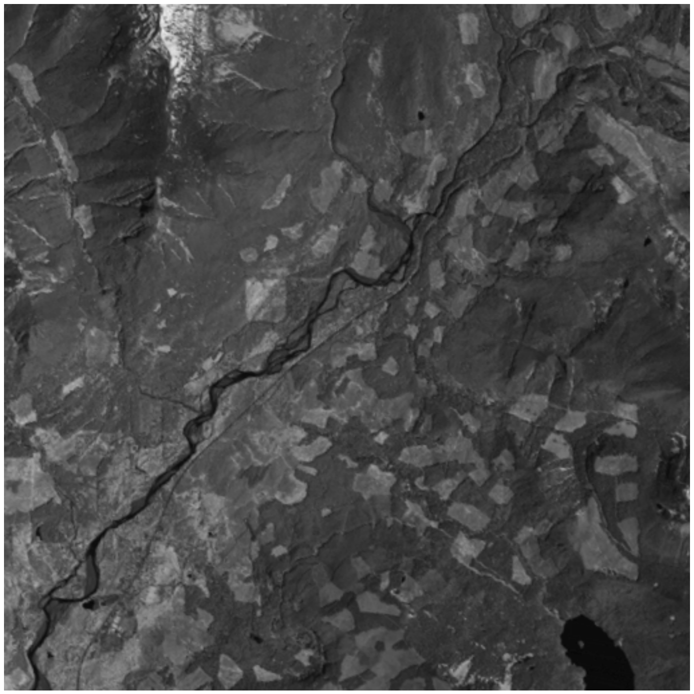
$$I * h\,(x,y) = \sum_{(u,v)\text{ in }N} I(u,v)\,.\,h(x-u,y-v)$$

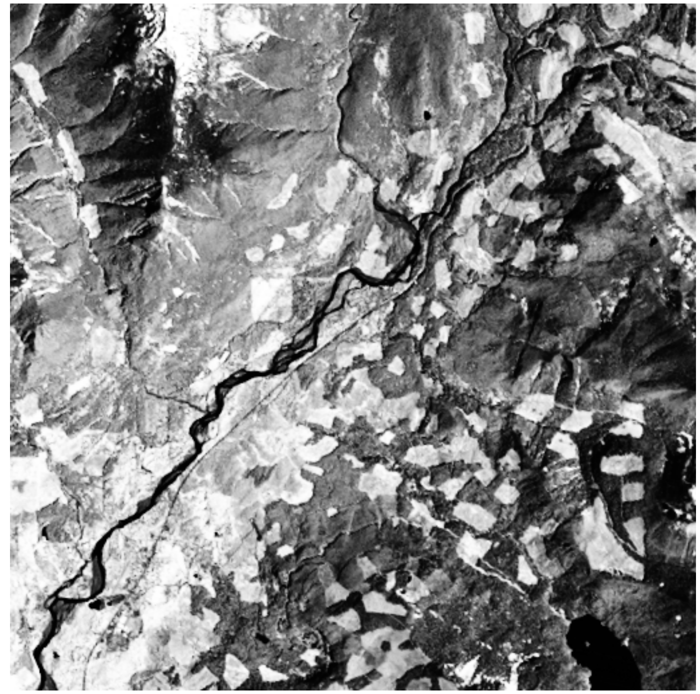
  - – Theorem / Fourier Transforms (F):

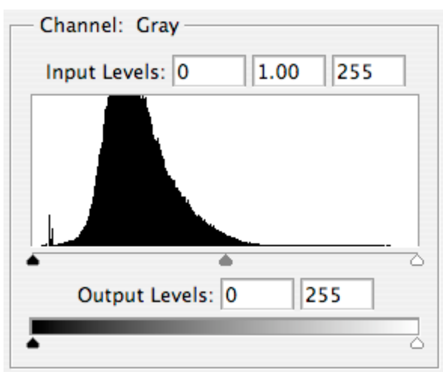
$$F\,(I_1 * I_2\,) = F(I_1)\,.\,F(I_2)$$

Image Enhancement

Histogram Equalization







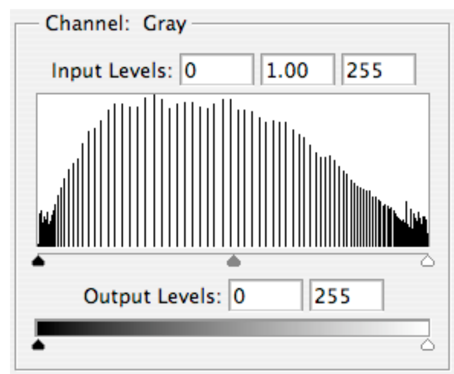
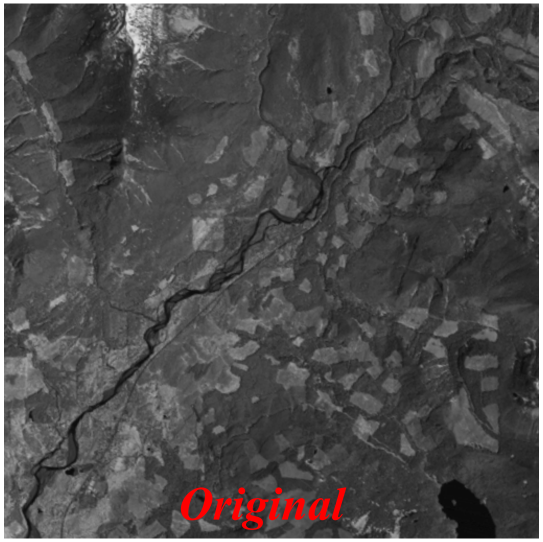
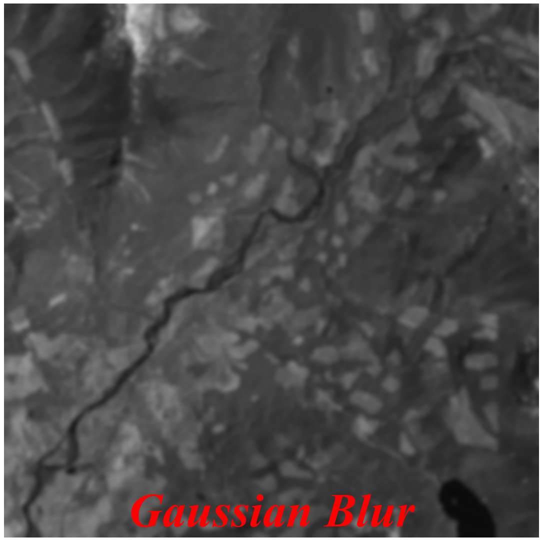
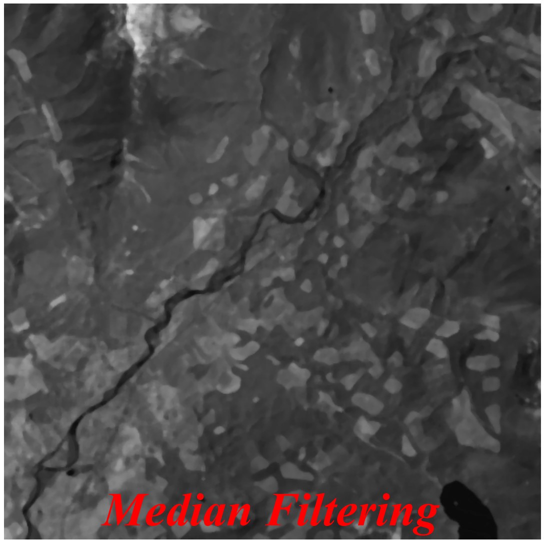


Image Smoothing





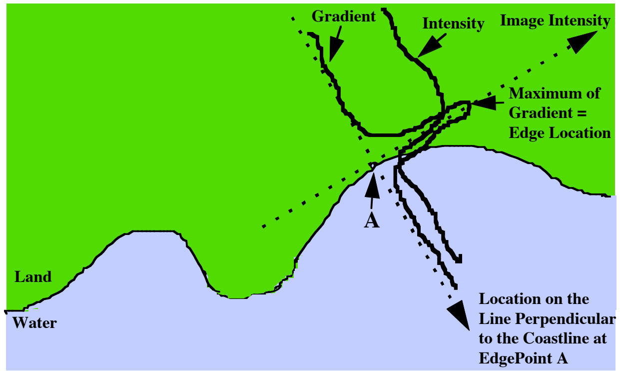


(Edge-Preserving Smoothing)

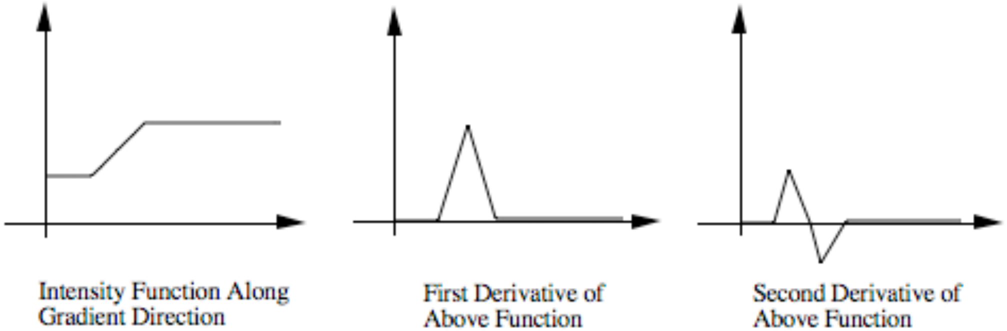
Edge Detection

Edge Detection

- Find "Jumps in Intensity", i.e. pixels where Gradient is Maximum



- Edge Detection Methods: Compute 1st and 2nd Derivatives
    - o Find Maxima of First Derivative
    - o Find Zeros of Second Derivative



Gradient Operator
(1st Derivative)

- Sobel Edge Detector (2 masks):

$$G_x = \begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix} \qquad G_y = \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix}$$

- Convolution of Gradient Operators with Image:
  - $\partial I/\partial x\ (x,y) = Gx * I\ (x,y) = \sum u \sum v\ [Gx(u,v)\ .\ I(x-u,y-v)]$
  - $\partial I/\partial y\ (x,y) = Gy * I\ (x,y) = \sum u \sum v\ [Gy(u,v)\ .\ I(x-u,y-v)]$

- Gradient of image I at Pixel (x,y):
  - Magnitude: $GI(x,y) = \sqrt{((Gx * I(x,y))^2 + (Gy * I(x,y))^2)}$
  - Direction: $Arctg(DGI(x,y)) = Gy * I\ (x,y)\ /\ Gx * I\ (x,y)$

- Variants: Prewitt (1 instead of 2), Roberts (2x2 neighborhood)

- Operators non Isotropic
  - o Isotropic Edge Detection with 1, 4 or 8 Masks, e.g., Laplacian:

$$L = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -8 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Example Gradient Computations

0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255
0	0	0	0	127	127	127	255	255	255

Gradient Magnitude:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} = 0$$

$$\begin{bmatrix} 0 & 0 & 127 \\ 0 & 0 & 127 \\ 0 & 0 & 127 \end{bmatrix} * \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} = 508$$

Gradient Direction:

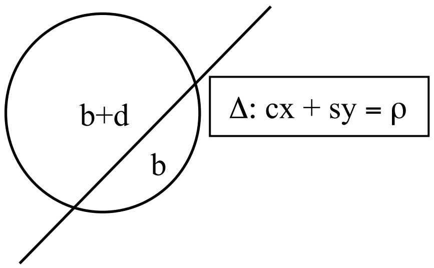
- Gx=508 ; Gy=0
- Arctg(Gy/Gx) = Arctg(0) = 0

  Normal to Edge => Vertical Edge

- Edge Pixel = Pixel where Gradient Magnitude is Maximum
- Can be determined by Thresholding Gradient Magnitude

Some Other Edge Detection Methods

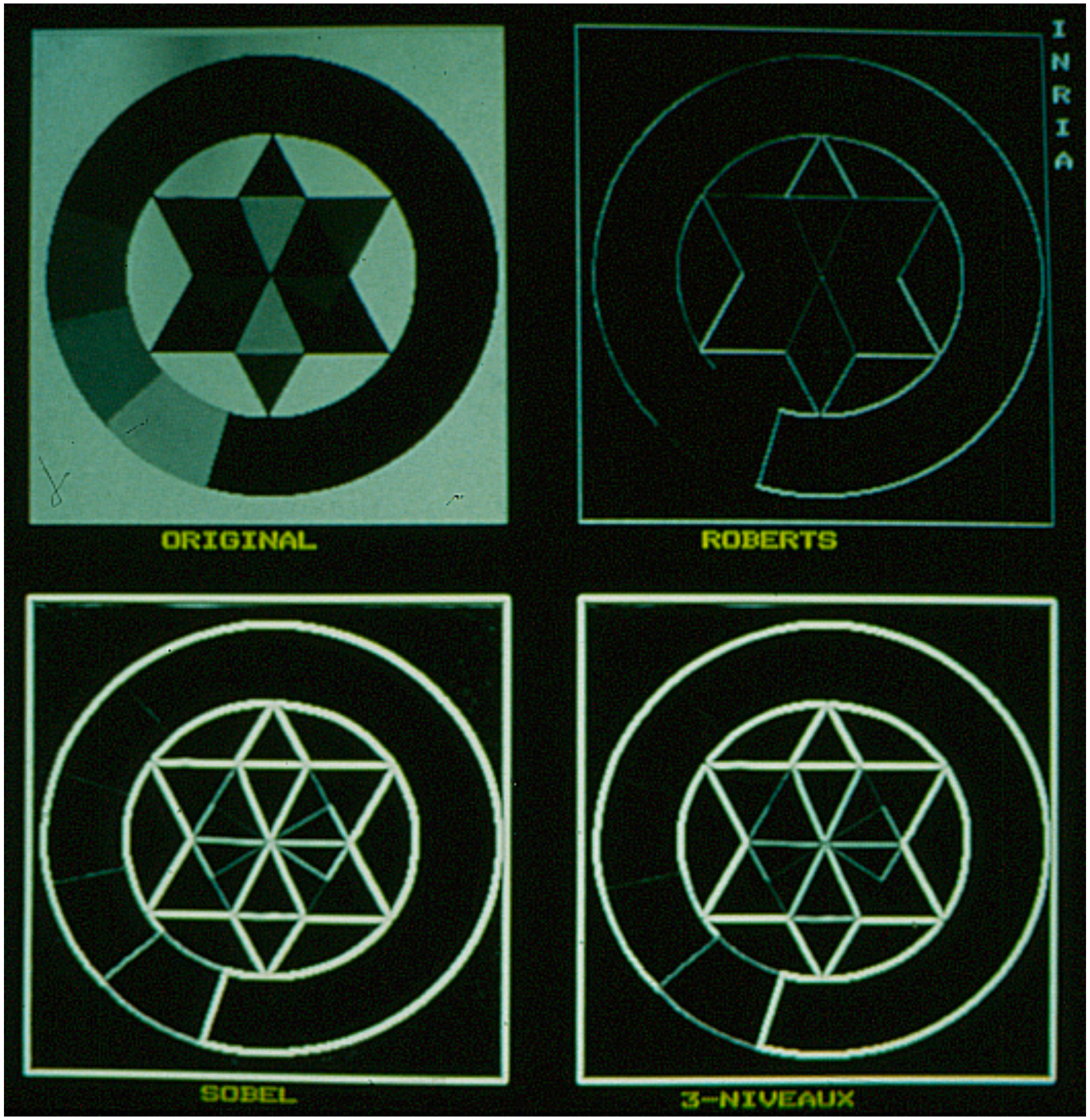
- Hueckel
  - o Approximate Edges with an “Edge Template”
  - o $S(x,y,c,s,r,b,d) = \begin{cases} b & \text{if } cx+sy \leq \rho \\ b+d & \text{else} \end{cases}$



- Marr & Hildreth
  - o Filter Image by Gaussian Filters of Various Variances (i.e., various frequencies)
  - o For each variance σ , find the zero crossings of the derivative of Image I filtered by G_σ(or εθu.: convolve I with 2nd derivative of G_σ or Laplacian)
  - o Laplacian approximated by Difference of 2 Gaussian filters

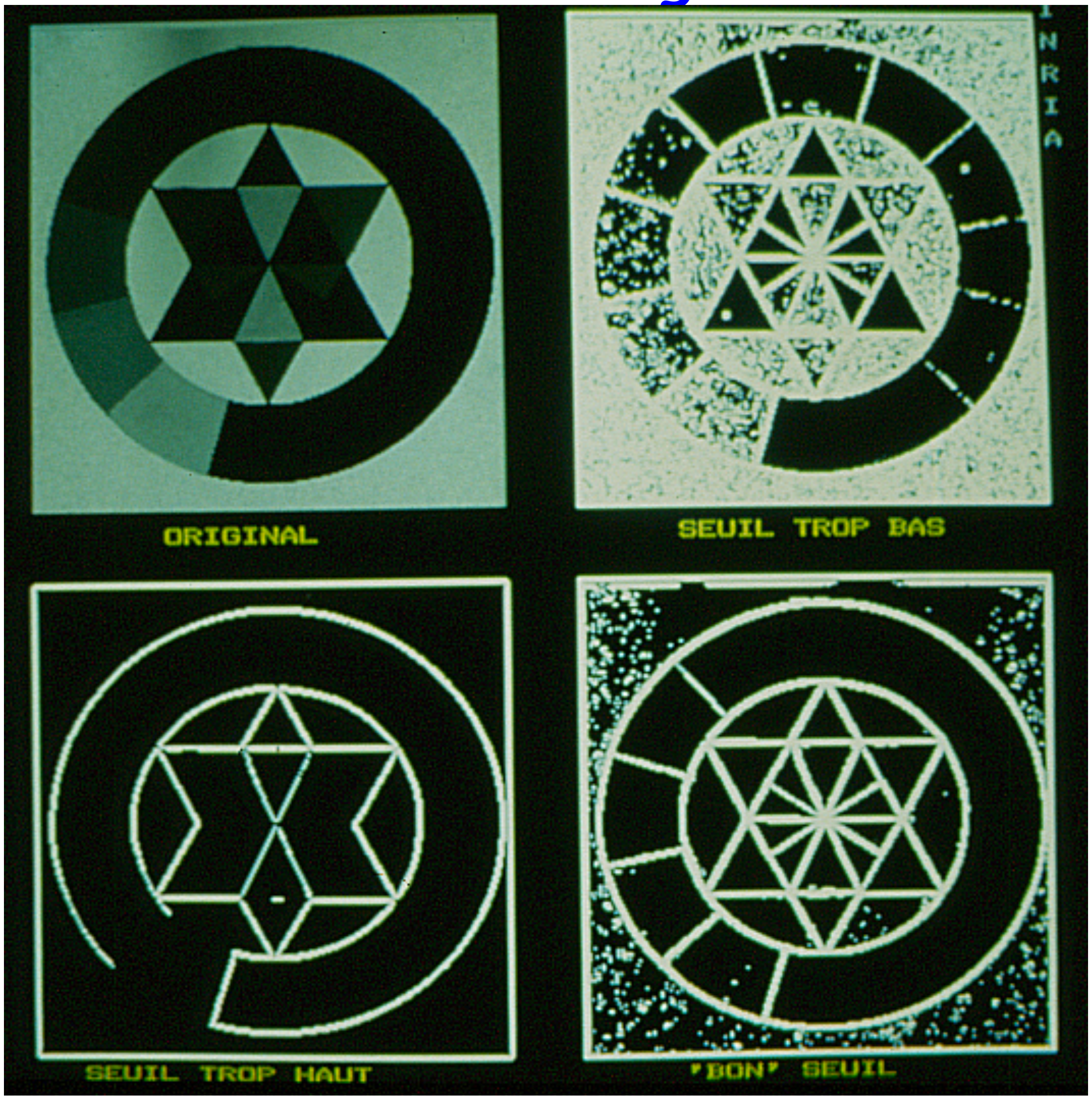
- Canny Edge Detector
  - Designed as an “Optimal Edge Detector” for following 3 criteria:
    - » Good Detection
    - » Good Localization (more Smoothing improves detection but hurts localization)
    - » Single Response per Edge
  - Steps:
    1. Gaussian Smoothing (Assumes Gaussian Noise)
    2. 2D First Derivative Gradient (e.g., Roberts or Sobel)
    3. Non-Maximal Suppression, i.e. keep Local Maxima in the Direction of the Gradient
    4. Hysteresis via 2 Thresholds, T_h and T_l; if $I < T_l$ => no-edge; if $I > T_h$ => edge; if $T_l \leq I \leq T_h$ => kept as an edge only if there is a path to an edge point

Edge Detection - Test Image



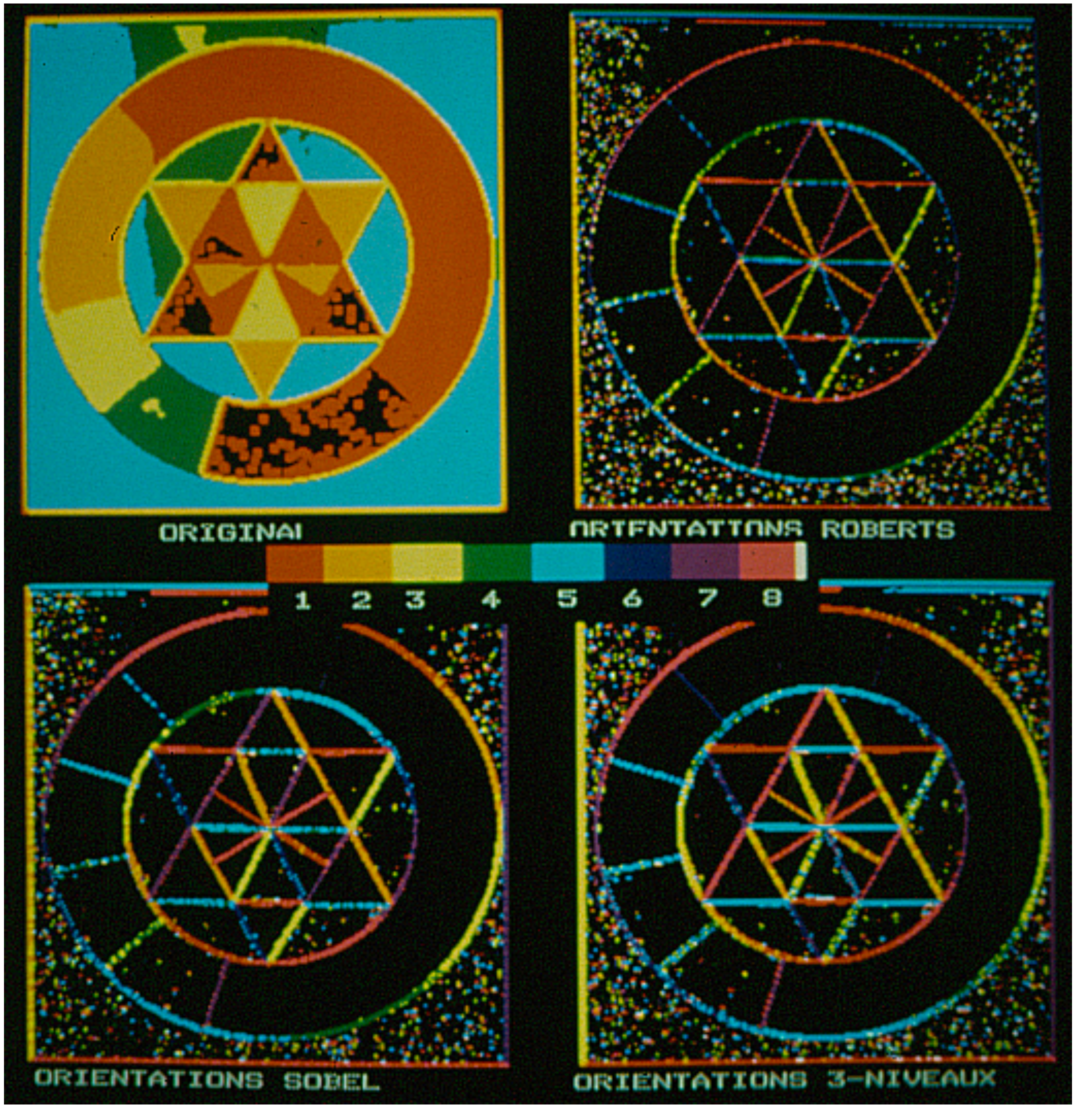
Gradient Thresholding

Test Image



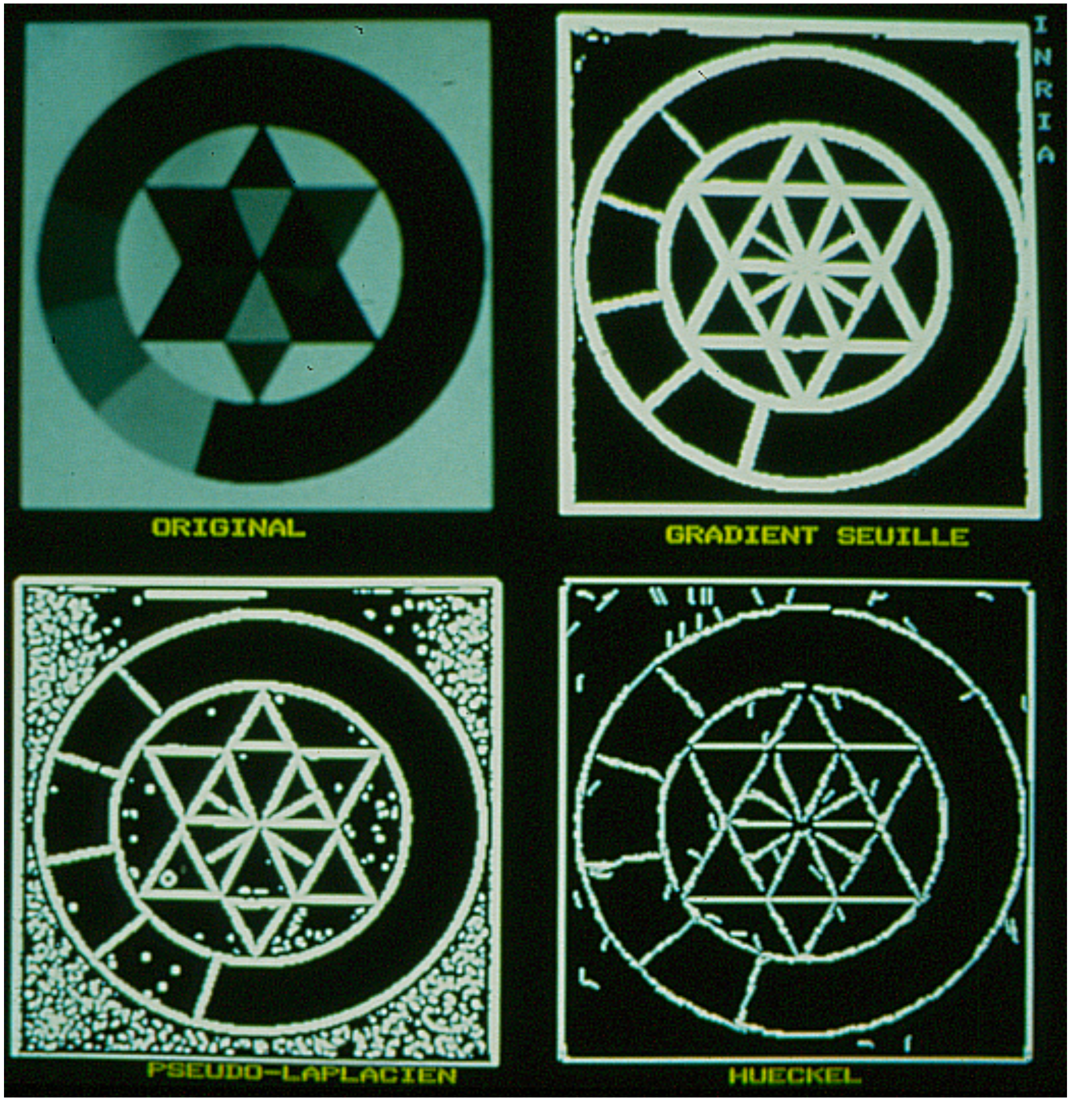
Gradient Directions

Test Image



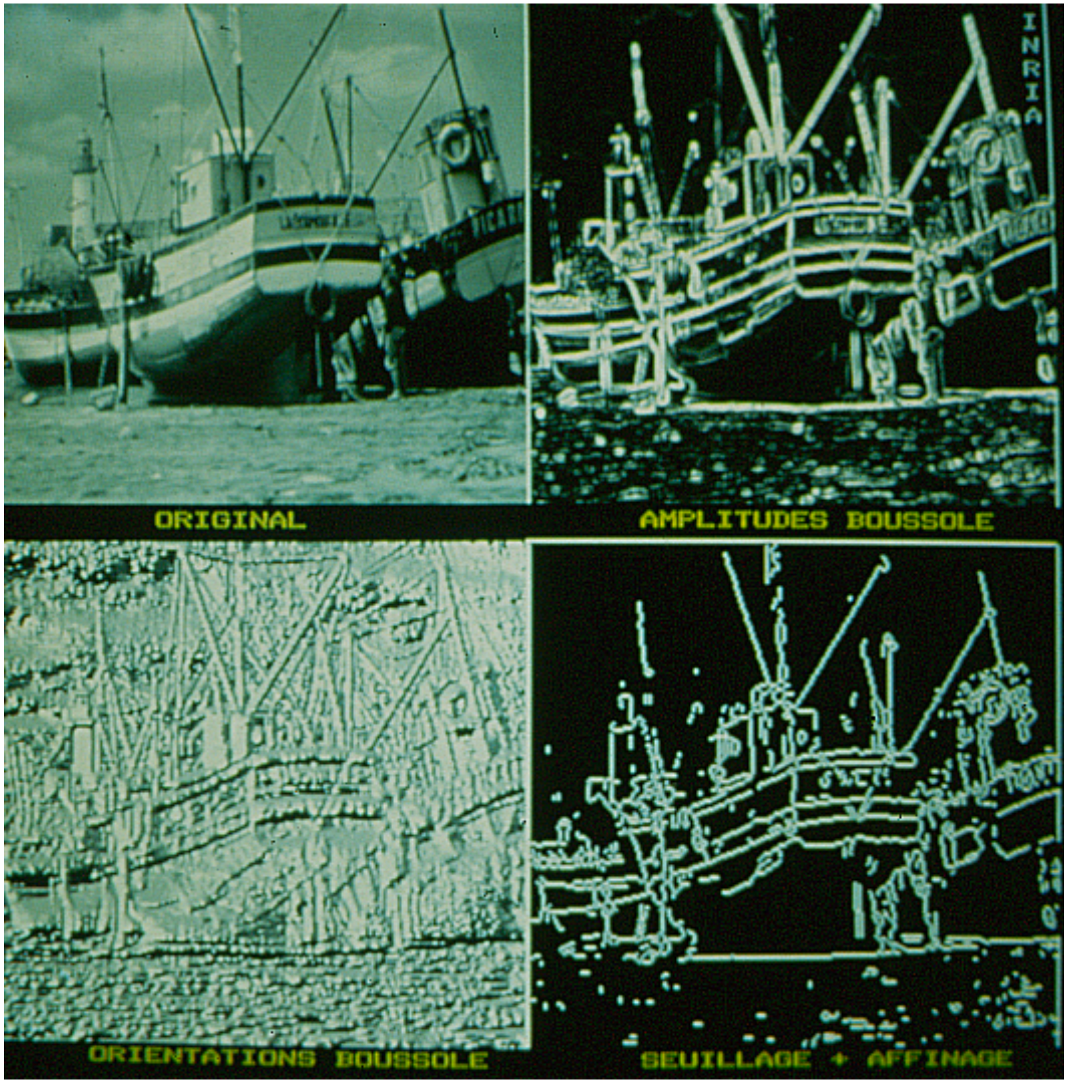
Other Edge Detectors

Test Image



Edge Detection Results

Boats



Fourier and Wavelet Analysis

Fourier Analysis

- Fourier Transform:
  - Decomposition of an Image in a Weighted Sum of Sinusoid Functions of Different Frequencies
  - $F(I)(x,y) = \iint I(u,v)\, e^{-\iota 2\Pi(ux+vy)}\, du\, dv$ => Weights

    $= \iint I(u,v) \cos(2\,\Pi(ux+vy))\, du\, dv + i \iint I(u,v) \sin(2\,\Pi(ux+vy))\, du\, dv$

    $= \text{Real}(F(I))(x,y) + i\ \text{Complex}(F(I))(x,y)$

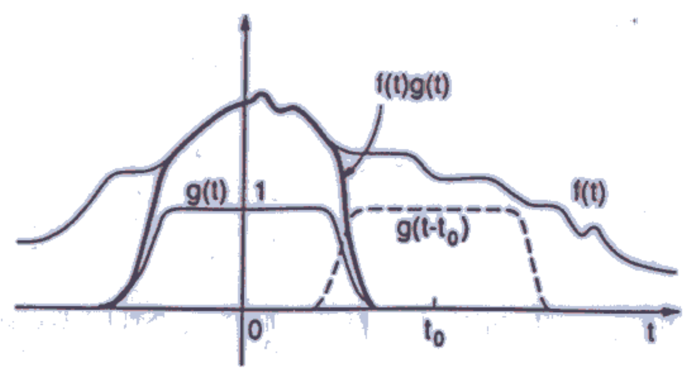
    $\{$ Amplitude $= \sqrt{(\text{Real})^2 + (\text{Complex})^2}$ and

    Phase = Arctg(Complex/Real)
  - Property: Fourier Transform of a Gaussian is a Gaussian
  - No Localization

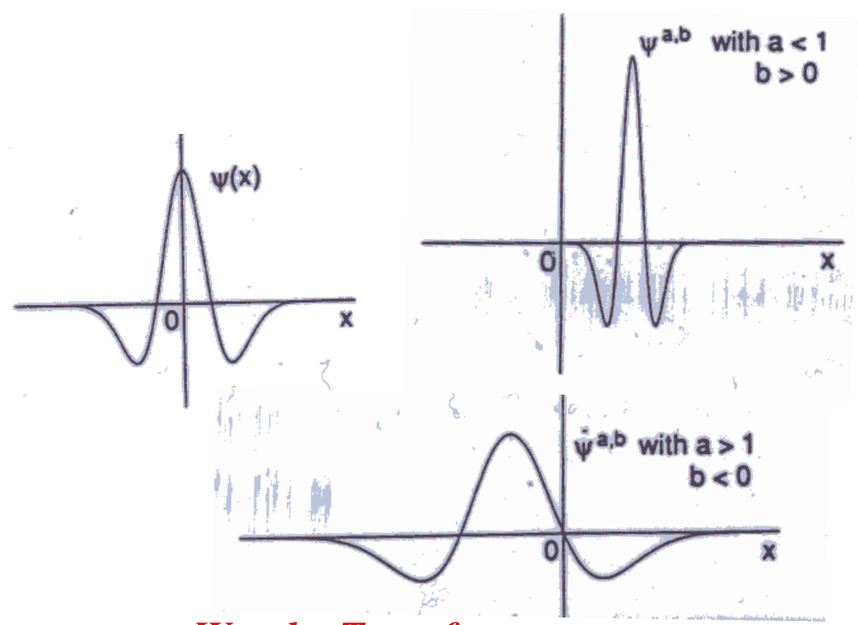
- Windowed Fourier Transform:
  - $WF(I)(x,y,p,q) = \iint I(u,v).G(u-p,v-q)\, e^{-\iota 2\Pi(ux+vy)}\, du\, dv$
  - Gabor Transform when G is a Gaussian function centered at every image point
  - Localization but G = Same Envelop for All Frequencies

Wavelet Analysis

- Wavelet Transform:
  - $Wav(I)(a,b) = 1/\sqrt{|a|}\iint I(u,v).W(u\text{-}b1,v\text{-}b2)\ du\ dv$
  - W is the “Mother Wavelet”
  - Localization (similar to Gabor)
  - Better Division of Space(Time)-Frequency Plane : Good for Short-Lived HF Components Superposed on Longer-Lived LF parts



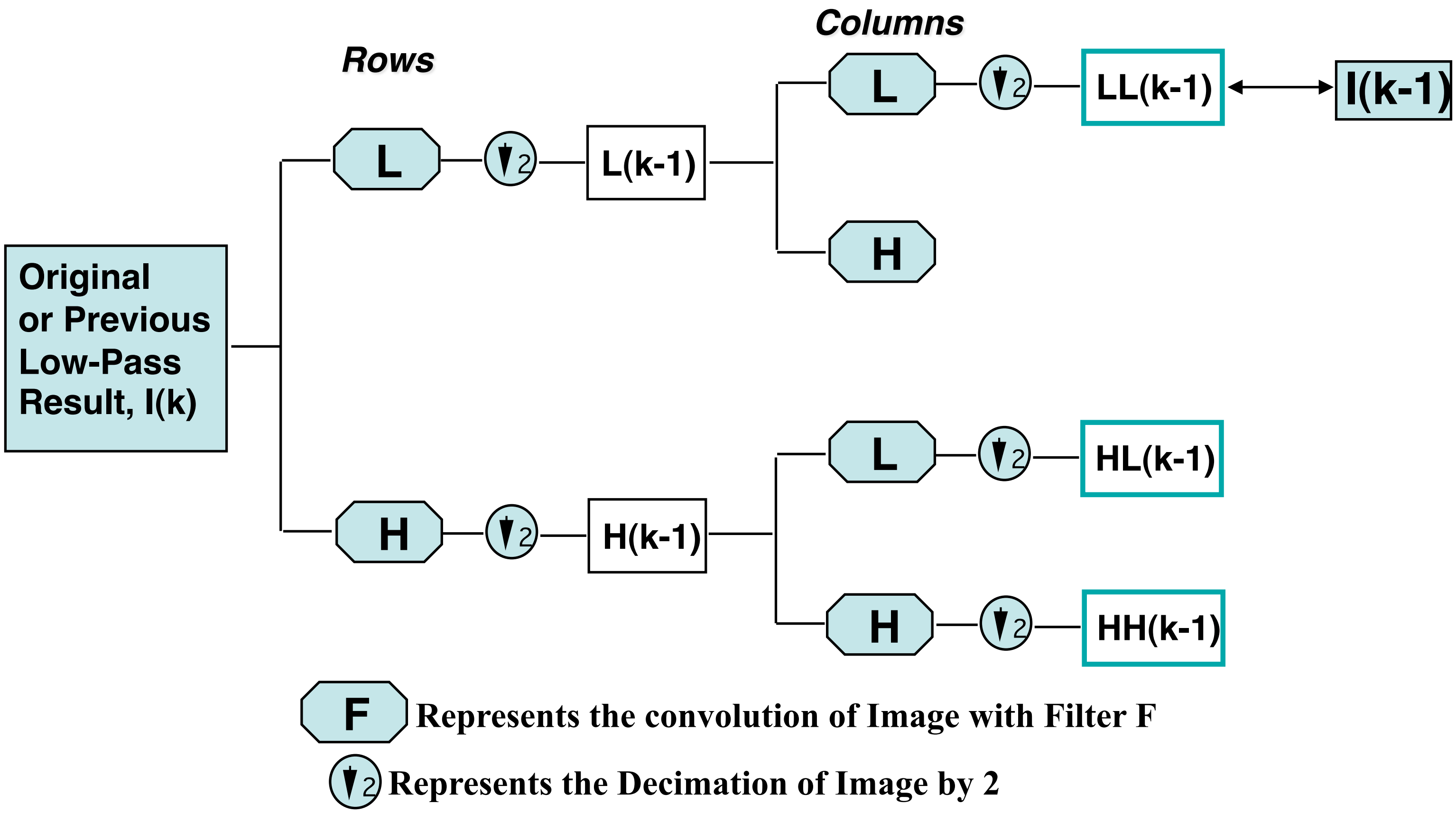
Windowed Fourier Transform



Wavelet Transform

Discrete Wavelets

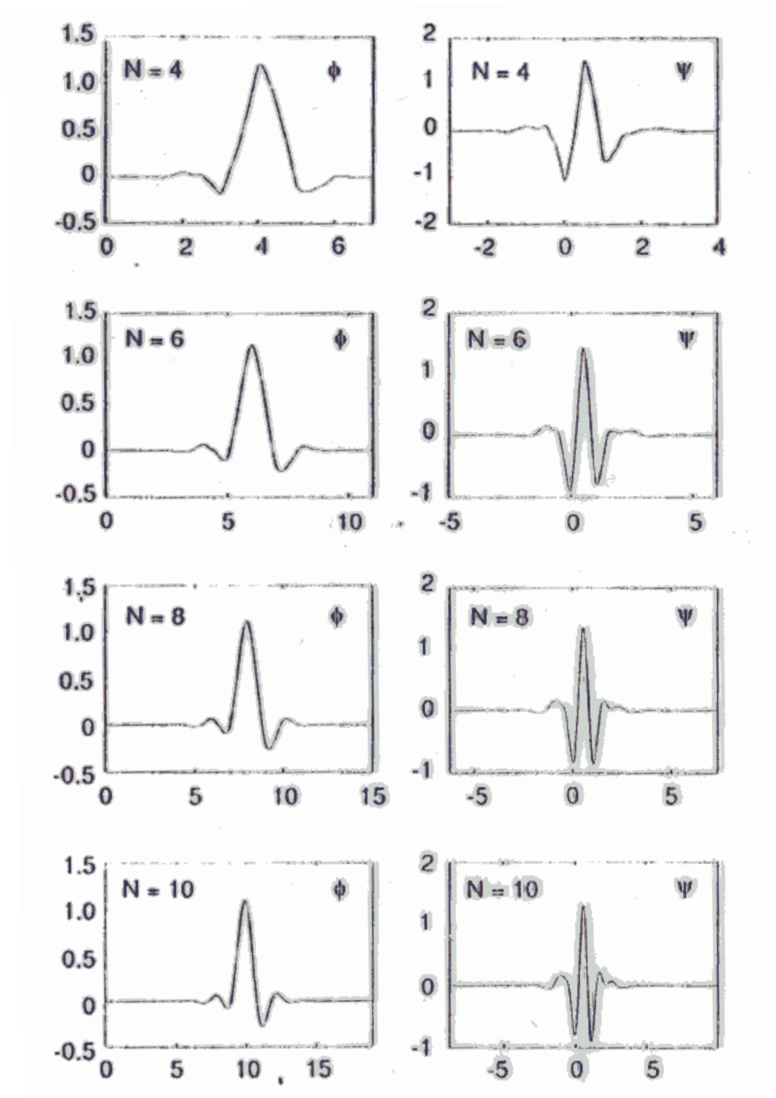
- Orthonormal Basis and Frames
  - Daubechies Wavelets
  - Mallat: Definition of Wavelets from a Scaling Function



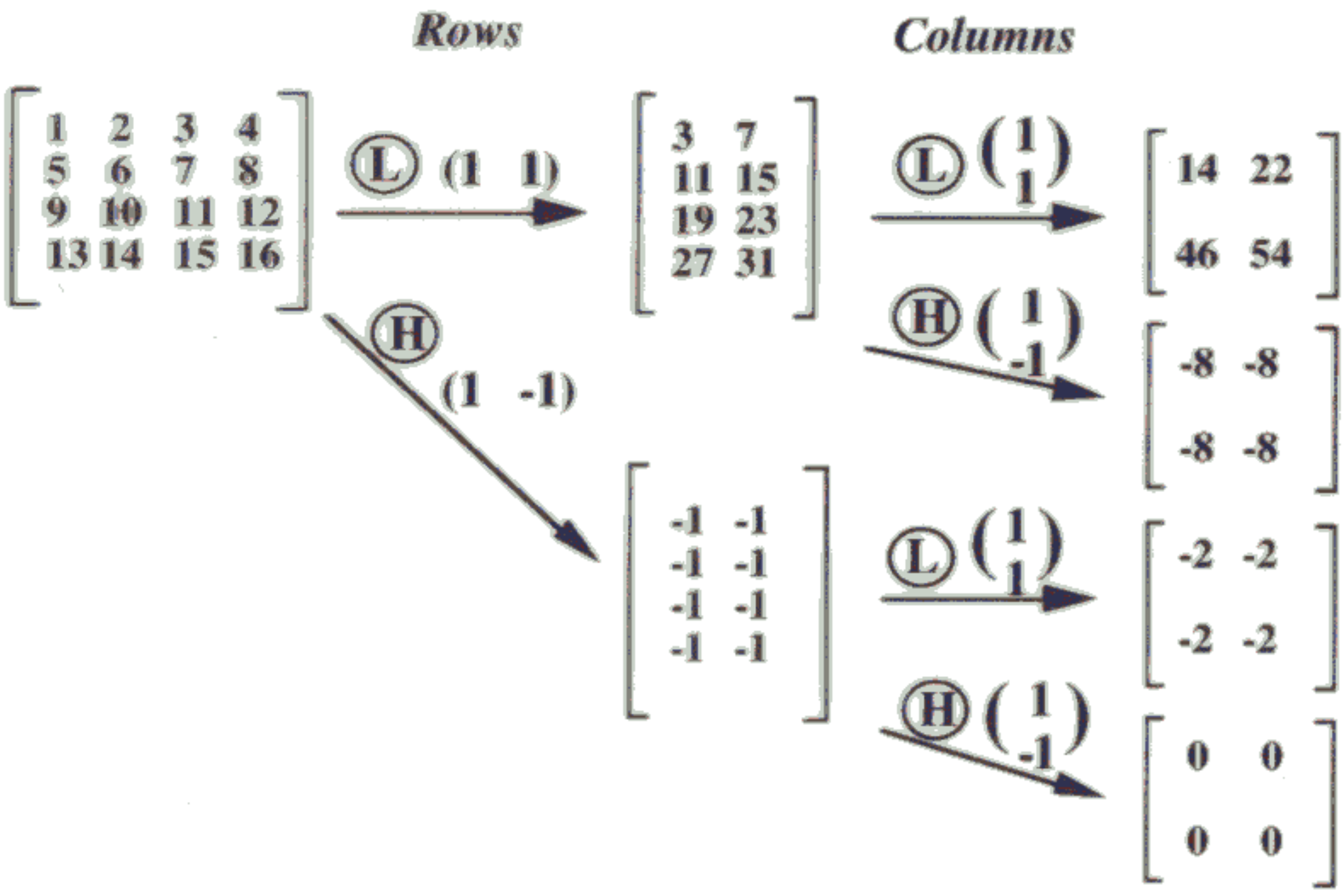
Represents the convolution of Image with Filter F

Represents the Decimation of Image by 2

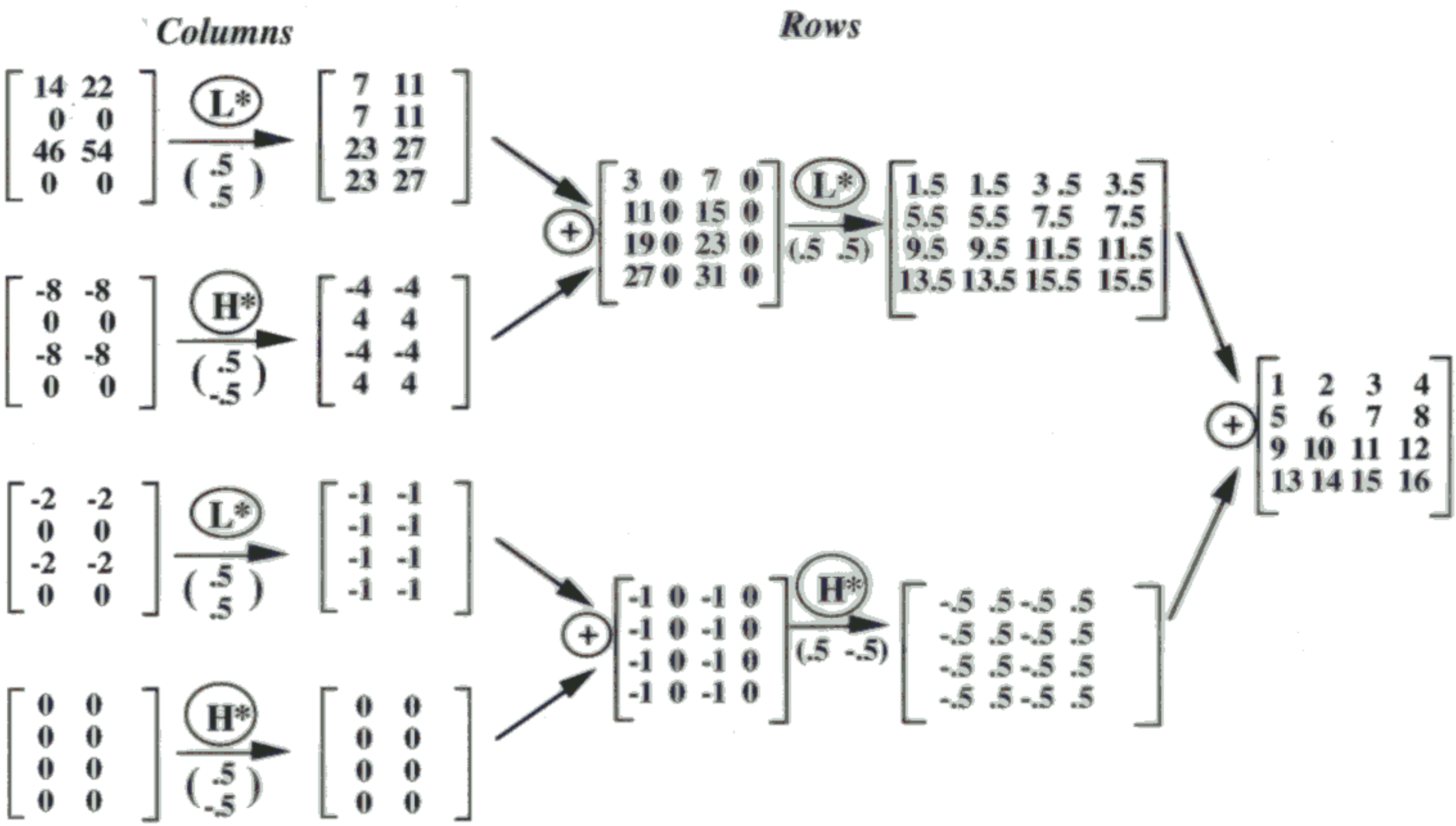
Daubechies Least Asymetric Wavelets



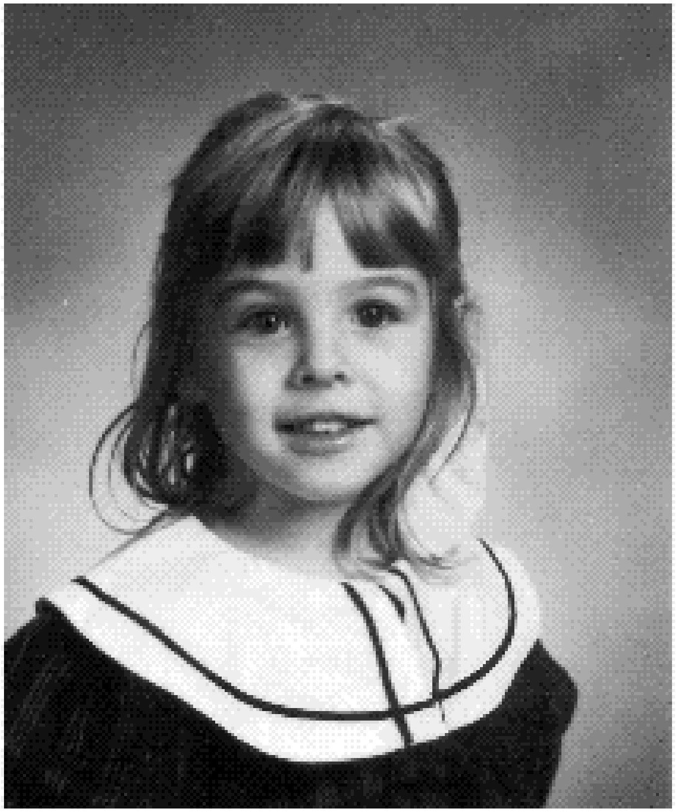
Example of 2D Wavelet Decomposition

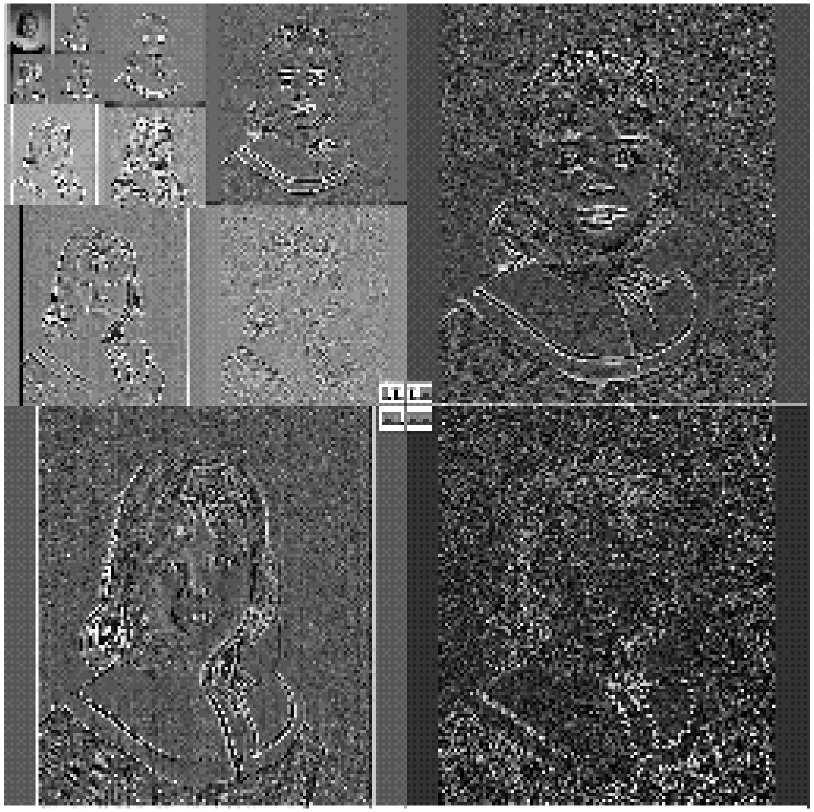


Example of 2D Wavelet Reconstruction



Example: Wavelets Transform





Applications Of Wavelets

- Image Compression
  - Provide a More Compact Representation of an Image
    - Lossy Compression (some visual quality is lost)
    - Lossless Compression
  - JPEG (Joint Photographic Experts Group) and JPEG-2000: Lossy Compression
    - JPEG: Compression based on Discrete Cosine Transform (DCT)
    - JPEG 2000: Compression based on Wavelets
- Image Registration
- Image Segmentation
- Image Fusion

Image Registration

Image Registration

- If I1(x,y) and I2(x,y): images or image/map

  Registration = Find the Mapping (f,g) which Transforms I1 into I2:

  $I2(x,y) = g(I1(fx(x,y),fy(x,y))$

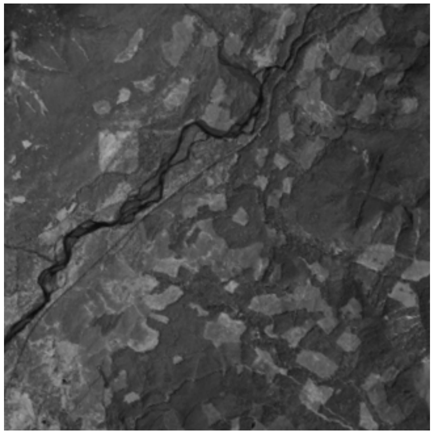
  » f : spatial mapping

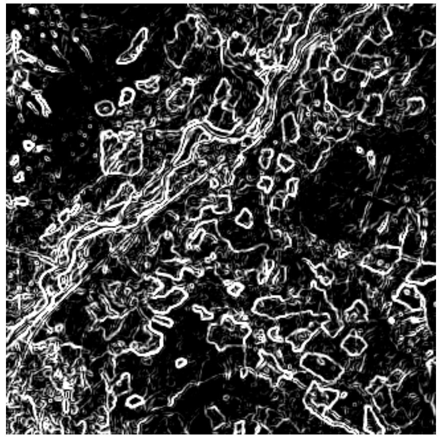
  » g: radiometric mapping

- Remote Sensing:
  - *Navigation* or Model-Based Systematic Correction
    - Orbital, Attitude, Platform/Sensor Geometric Relationship, Sensor Characteristics, Earth Model, ...
  - *Image Registration* or Feature-Based Precision Correction
    - Navigation within a Few Pixels Accuracy
    - Image Registration Using Selected Features (or Control Points) to Refine Geo-Location Accuracy

Image to Image Registration

Correlation of Edge Features



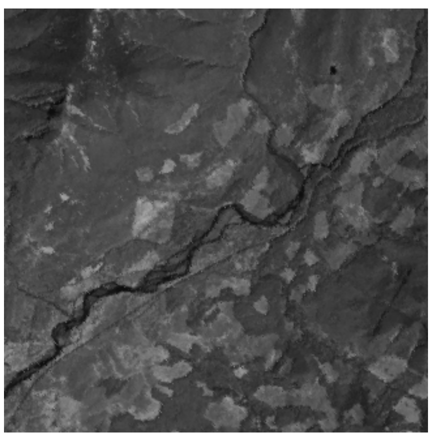


Incoming Data → Image Characteristics (Features) Extraction

Feature Matching

Compute Transform

- Multi-Temporal Image Correlation
- Landmarking
- Coregistration



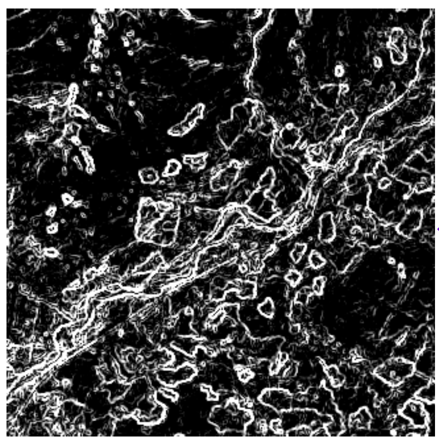
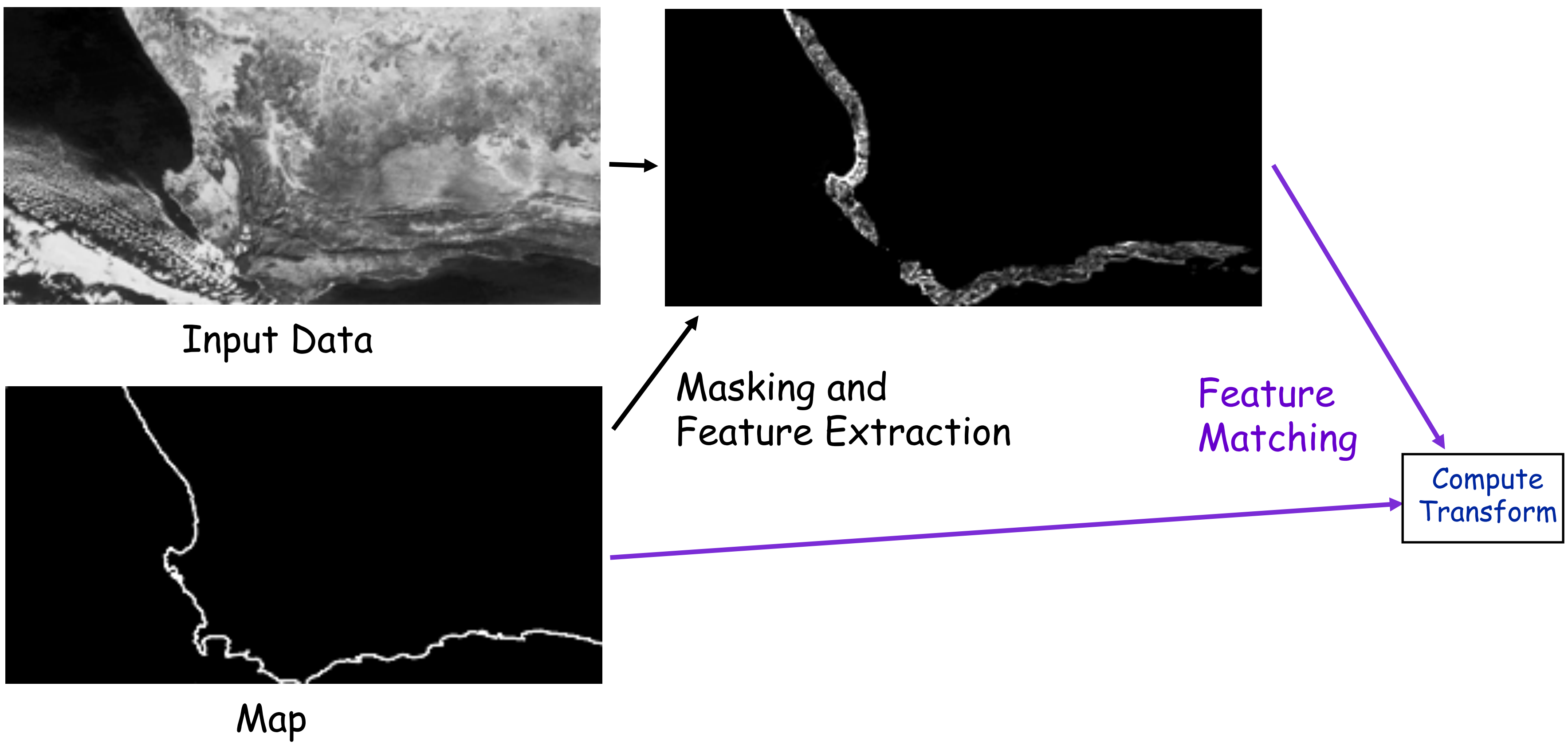
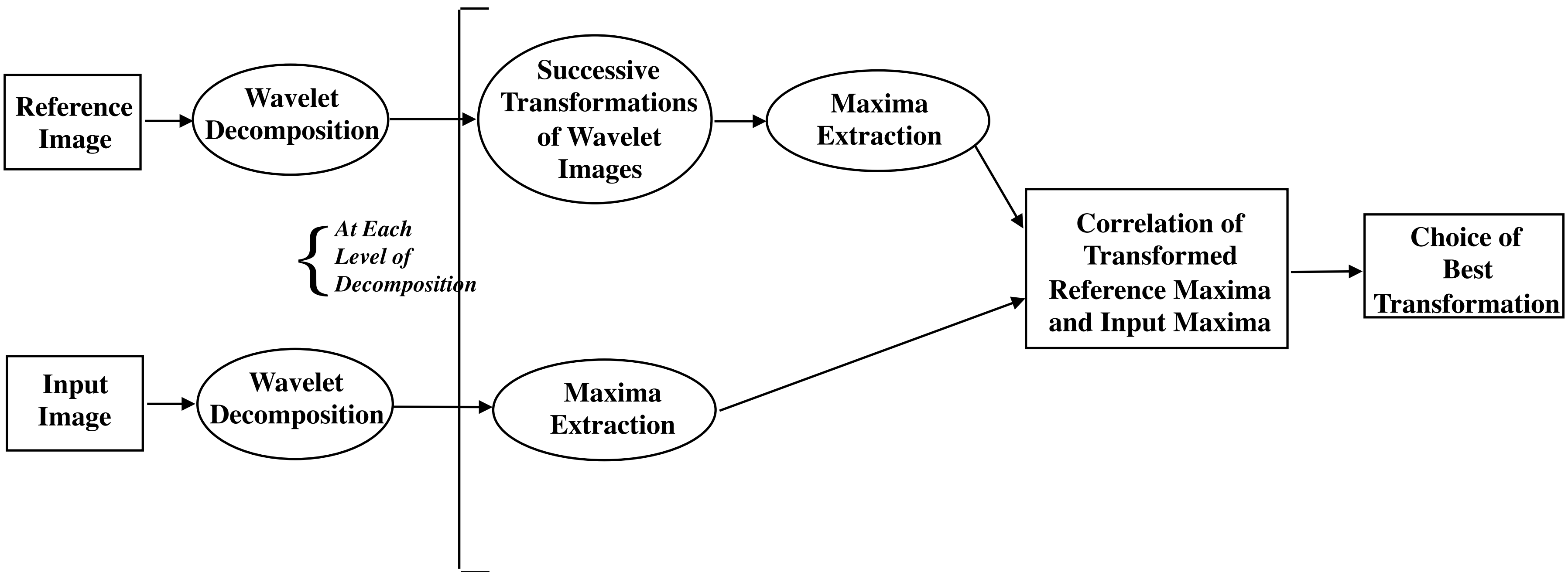


Image to Map Registration

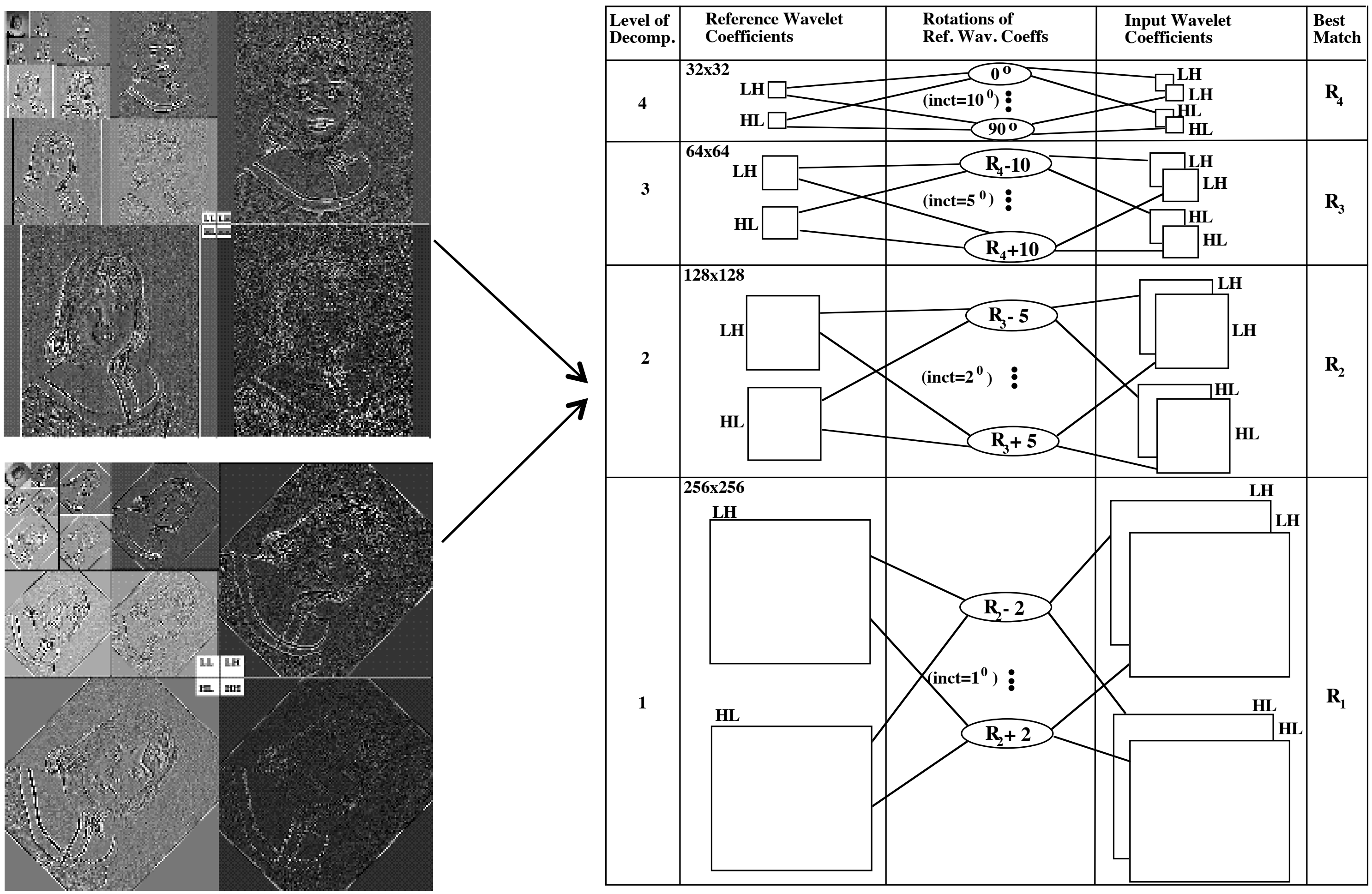
Correlation of Edge Features



Application of Wavelets to Image Registration



Multi-Resolution Wavelet Registration

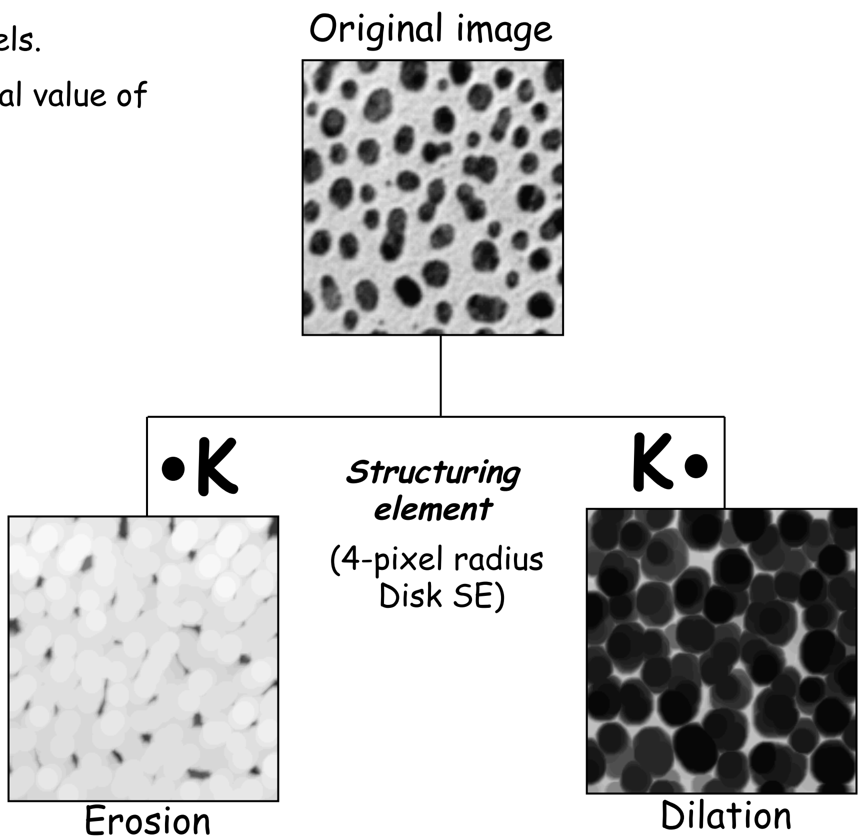


Mathematical Morphology

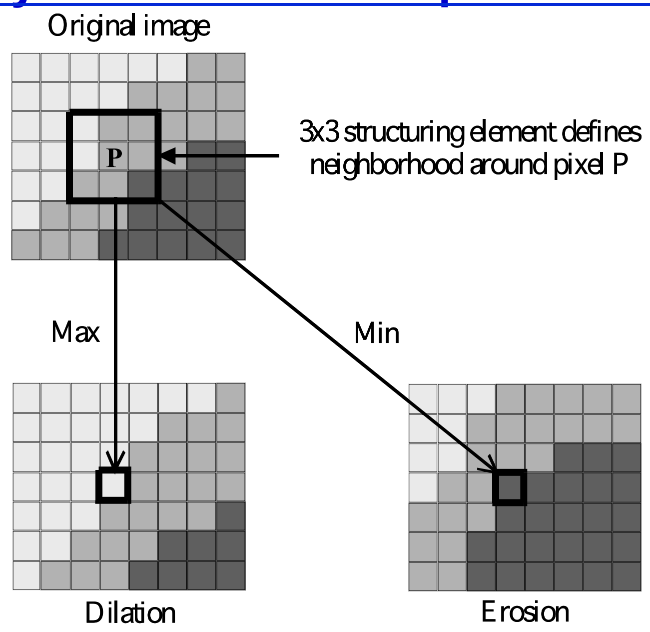
Mathematical Morphology Concept

Mathematical Morphology (MM) Concept:

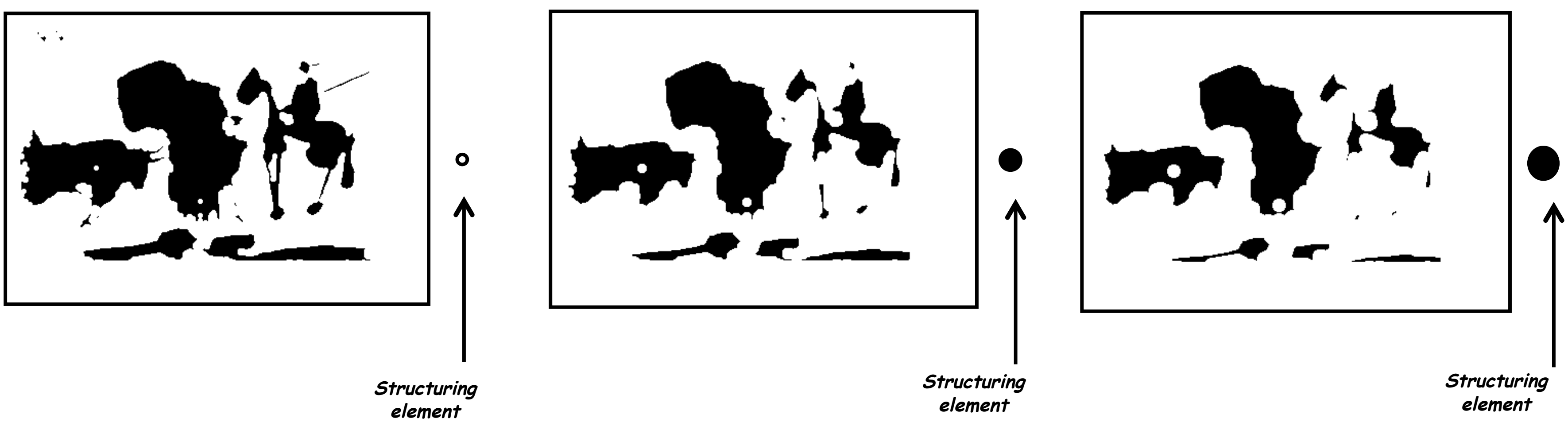
- Nonlinear *spatial-based* technique that provides a framework.
- Relies on a *partial* ordering relation between image pixels.
- In greyscale imagery, such relation is given by the digital value of image pixels



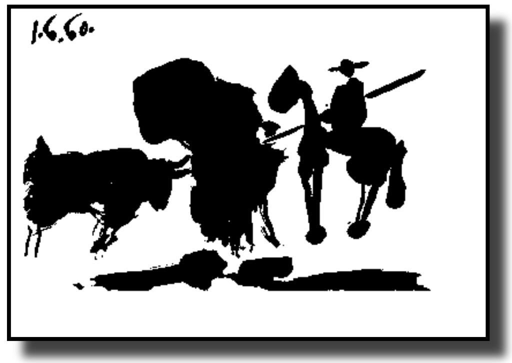
Greyscale MM Basic Operations:

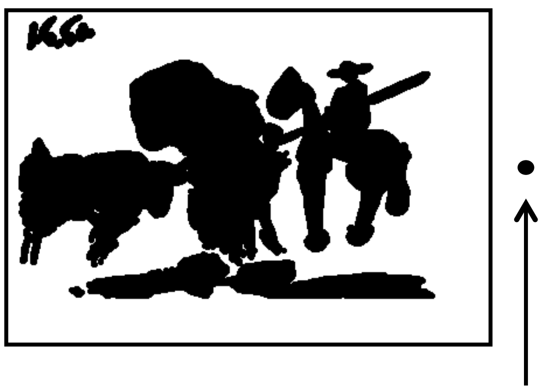


Binary Erosion

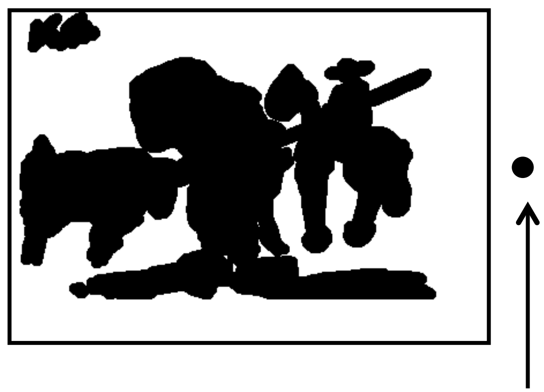


Binary Dilation

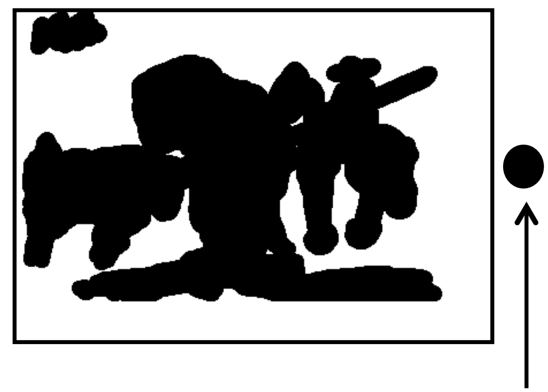




Structuring element

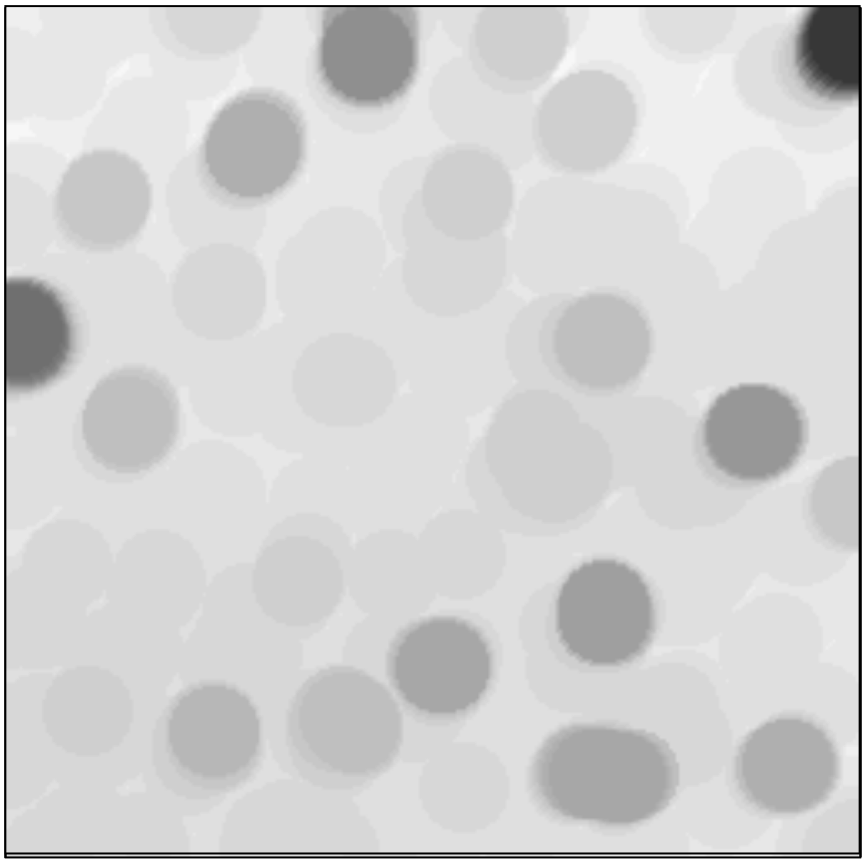


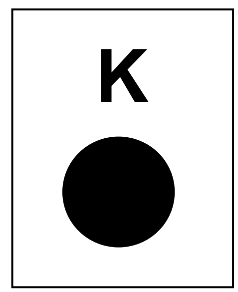
Structuring element



Structuring element

Combined Operations, e.g. Erosion + Dilation = Opening





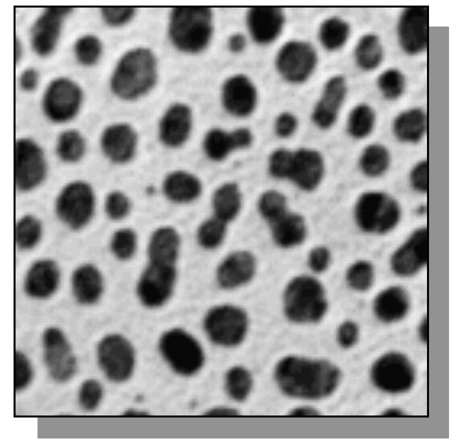


Image Segmentation

Image Segmentation

- **Image or Region Segmentation** is the process that generates a spatial description of the image as a set of specific parts, regions or objects.

- Image divided into groups of pixels that are homogenous for a given criterion
  - o Contrast with surroundings: ***edge-based segmentation***

    Examples: **Edge following, line or curve fitting**, etc.
  - o Similar properties, gray level, color,etc.measured by some local statistics such as means, variance, etc.: ***region-based segmentation***

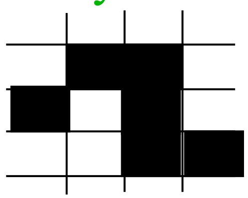
    Examples: **Region Growing, Region Splitting, Split and Merge, Relaxation, Watershed**, etc.
  - o Remark: Image Classification = Pixel-Based Method (e.g., **Neural Networks**)

- Segmented Output => Higher-Level Image Interpretation Process, part of Computer Vision or Image Understanding.

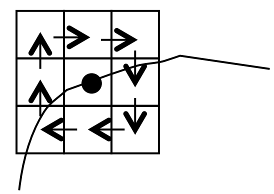
Edge Following

- Prior Processing: Edge Detection and Thresholding => Choose Starting Point above Threshold

- Various Methods for Edge Following, e.g.:
  - Line by Line Edge Following: Label all Contours

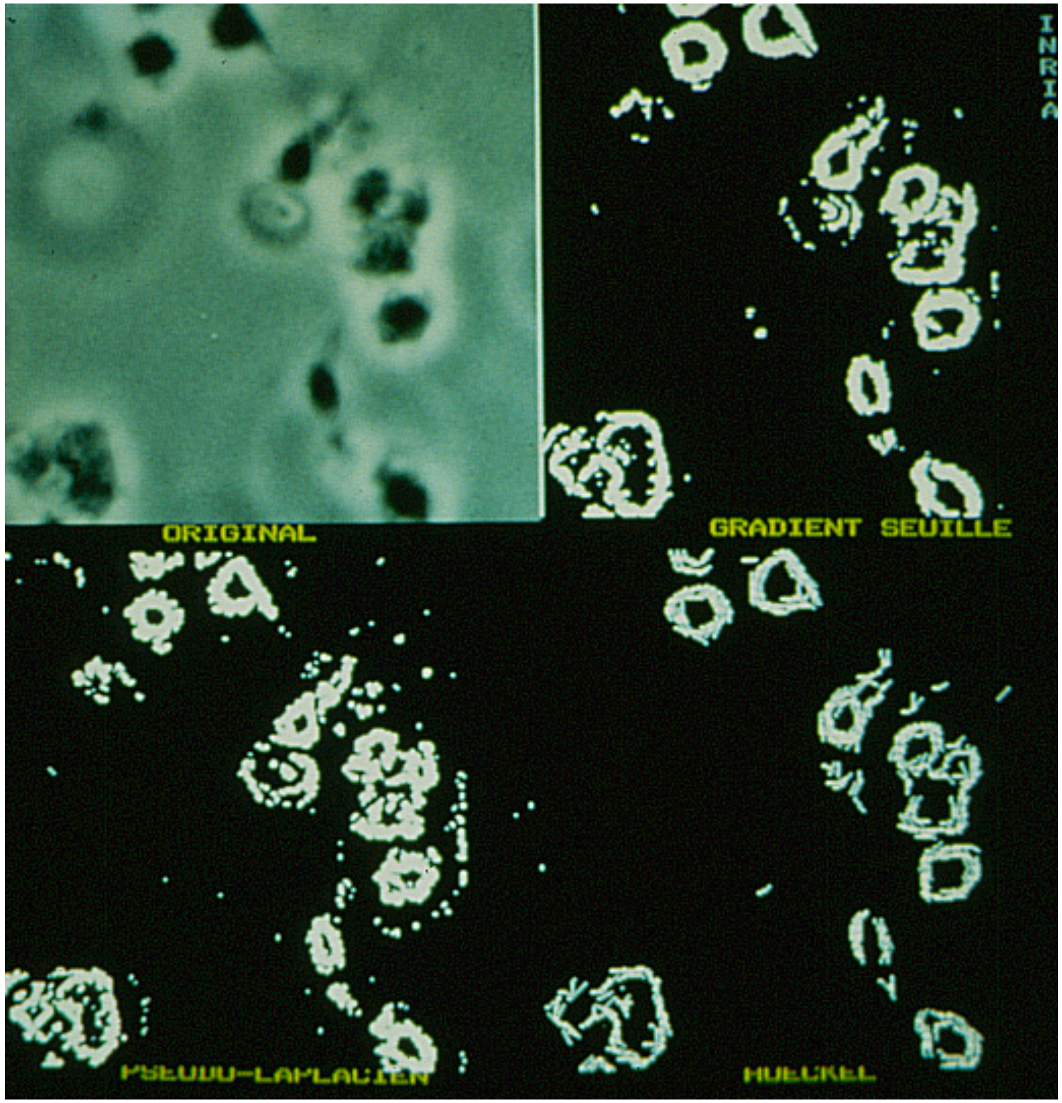


Give the Same Label to all Connected Pixels

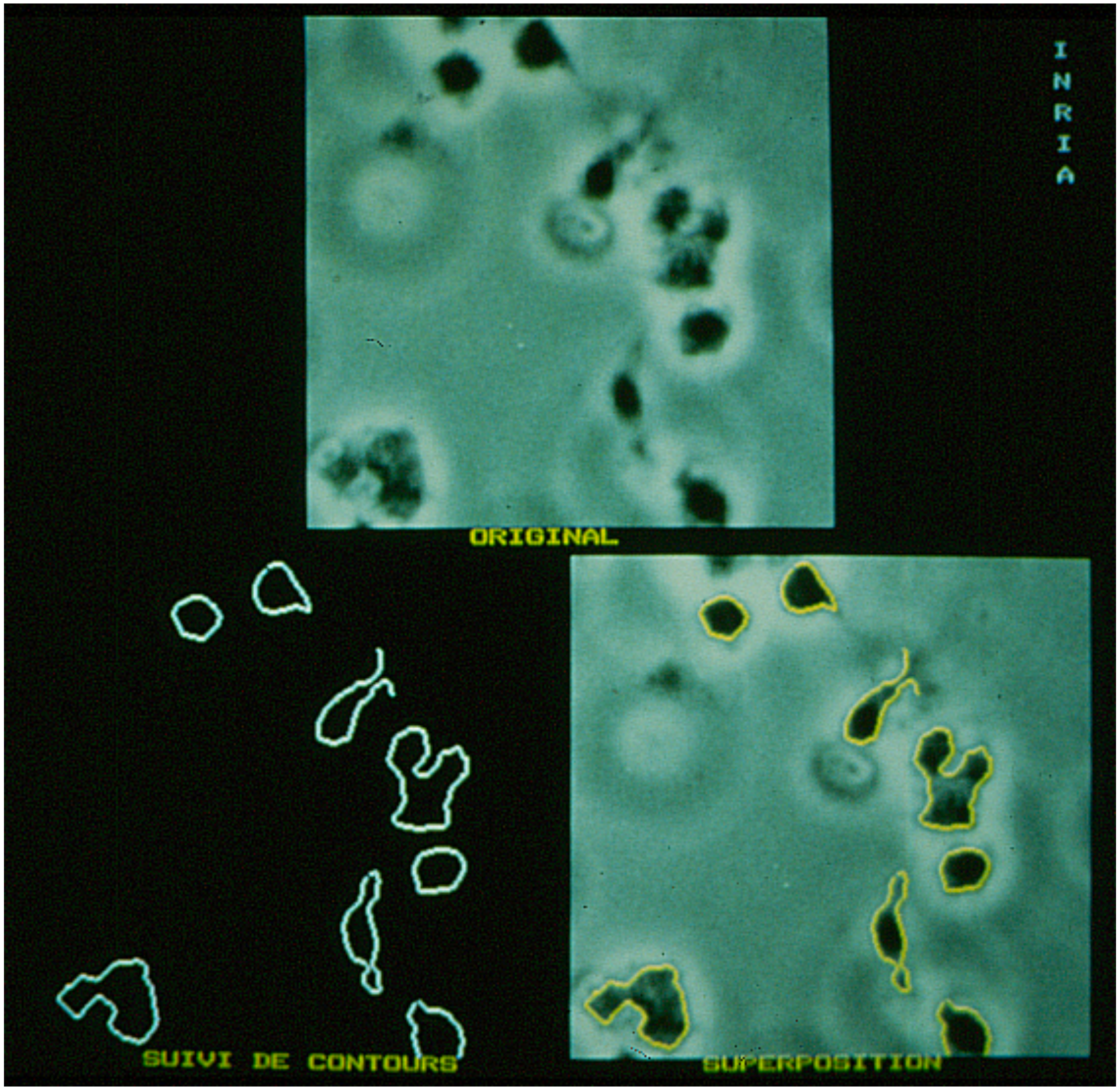


  - Contour Following
    1. Starting Point P_0 with Gradient Magnitude above Threshold
    2. In Neighborhood (4 or 8 pixels) Centered around P_0, Search in Circular Pattern => 1st point above Threshold and Gradient Direction Compatible with P_0
  - Graph Traversal
    - All Pixels whose Magnitude is above Threshold represent the Nodes of a Graph
    - Define a Cost Function Based on Gradient Magnitudes and Orientations
    - Contour Extraction Performed by Finding Path of Optimum Cost

Blood Platelets Extraction



Blood Platelets Extraction



<u>Algorithm:</u>

1. Histogram Equalization
2. Sobel Edge Detection
3. Dilation
4. Circular Edge Following

Line and Shape Detection

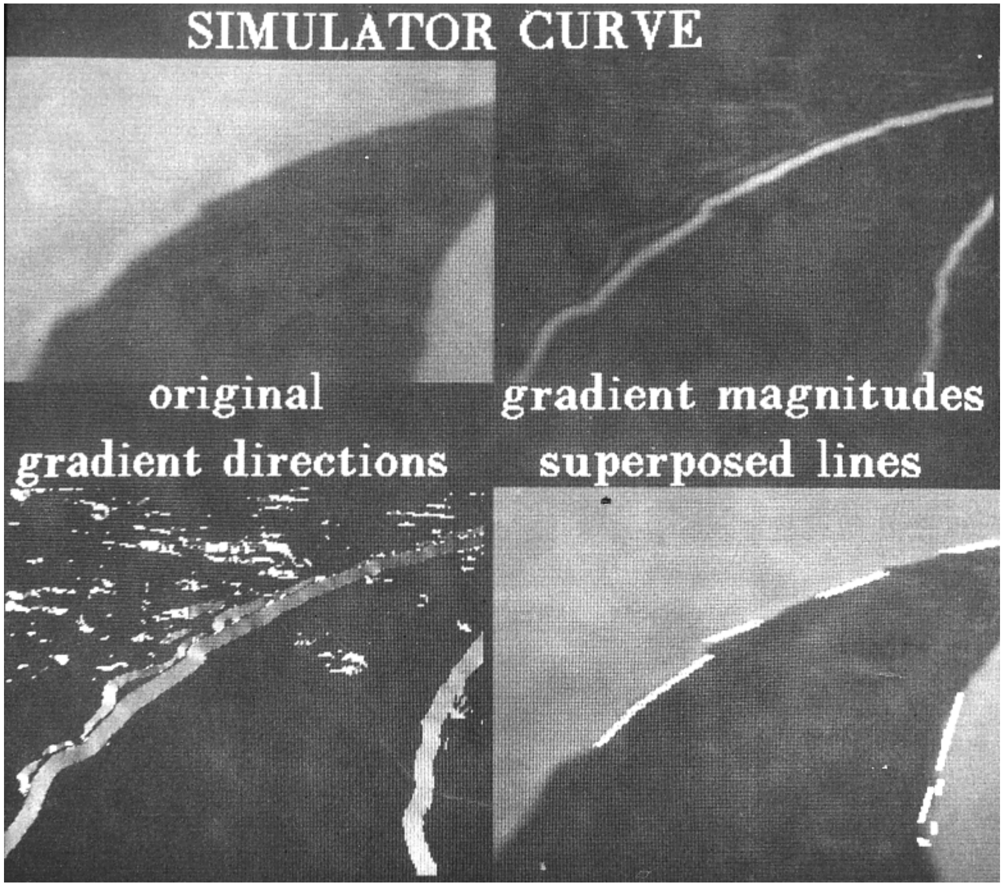
- Build upon Edge Detection results
  - Let us call (G,D) the edge magnitude and direction images of an image I

  - **Hough Transform for Line Detection**
    - Every line can be represented as: $x\cos\Theta + y\sin\Theta = \rho$
    - Create an Accumulator:
      - For each (x,y) for which G > threshold, compute $\rho = x\cos D + y\sin D$
      - Increment the counter of (ρ, D) in the accumulator
      - The pair (ρ, Θ) corresponding to the maximum counter represents the strongest line in the image
    - Idea: Strong Lines in (x,y) space correspond to Maxima (or Peaks) in (ρ, Θ) space
    - Can be Used to extract other shapes, e.g. ellipses

Line Detection for Road Following
(Autonomous Land Vehicle, ALV)

<u>**Bootstrap Algorithm:**</u>

1. **Sobel Edge Detection**
2. **Segment Orientation Histogram**
3. **Create Magnitudes Images for each "Orientation Region"**
4. **For each "Orientation Image", Compute Hough Transform => Strongest Line**
5. ***Label All Lines According to World Model***

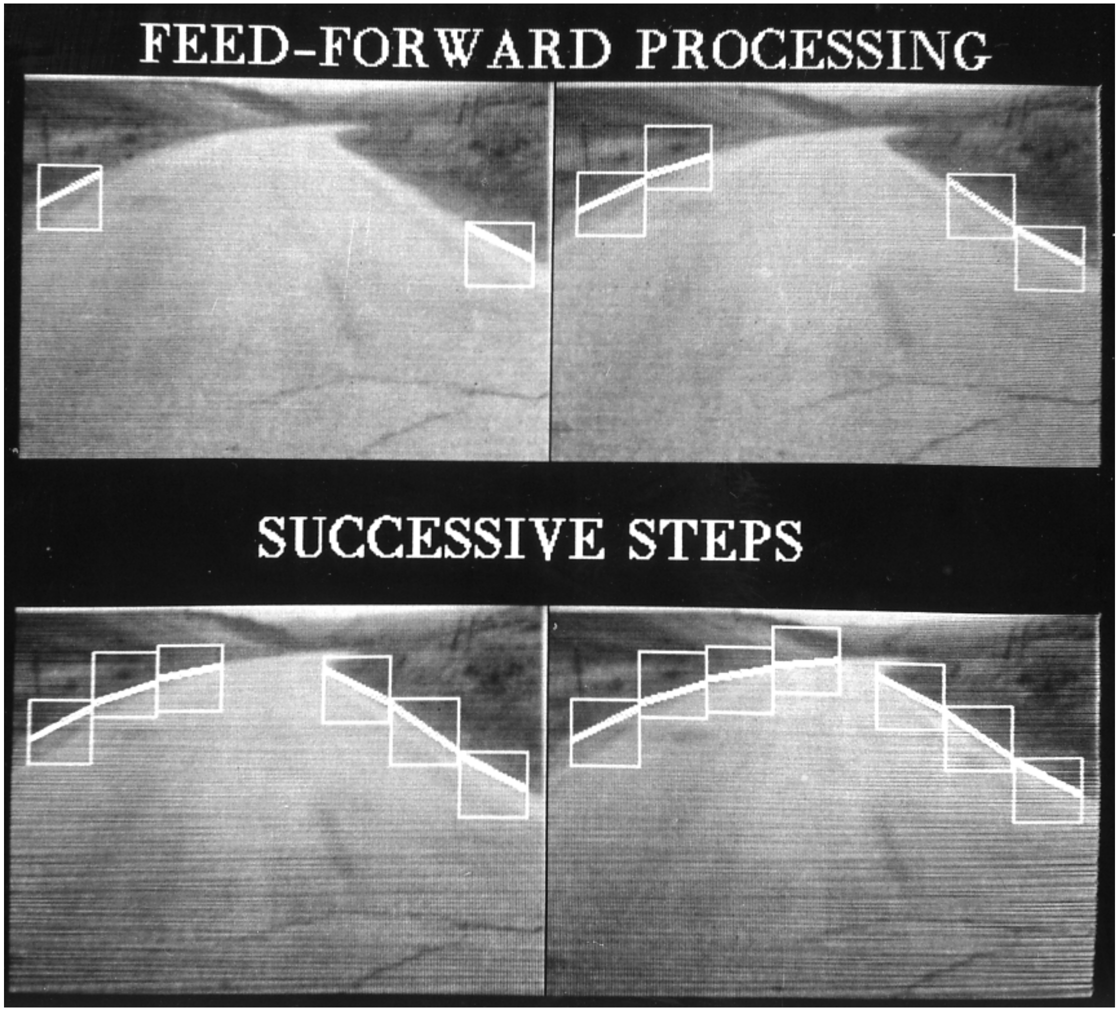


Line Detection for Road Following
(Autonomous Land Vehicle, ALV)

<u>**Feedforward Algorithm:**</u>

Strongest Orientation Known from Bootstrap Step

1. **Sobel Edge Detection**
2. **Segment Orientation Histogram**
3. **Create Magnitudes Images for Strongest "Orientation Region" from Bootstrap**
4. **For Strongest "Orientation Image", Compute Hough Transform => Strongest Line**

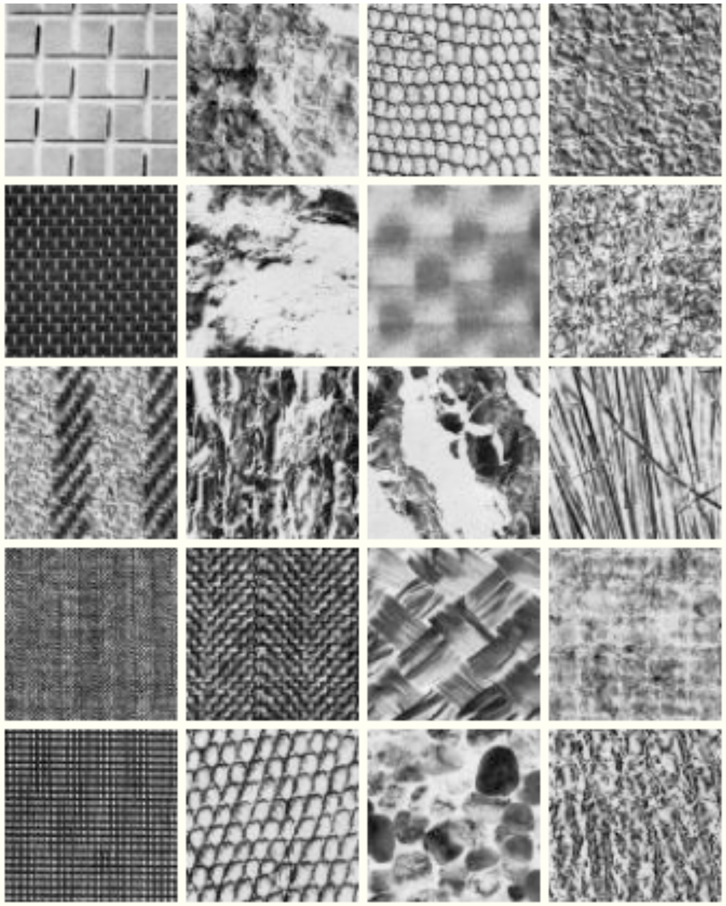


Region-Based Segmentation

- Methods
    - Region Growing
    - Region Splitting
    - Split and Merge
    - Relaxation
    - Watershed Method
    - Means Cut
    - etc.
- Parameters
    - Mean and Variance
    - Edge Magnitudes
    - Texture
        - ✓ Cooccurrence Matrix
        - ✓ Textural Edgeness
        - ✓ Filter Banks
        - ✓ Local Spatial Frequency Analysis, Gabor Filters and Wavelets
        - ✓ Mathematical Morphology
    - etc.

What is Texture ?

- (Rosenfeld and Kak) “Visual Textures are complex visual patterns composed of entities, or subpatterns (textons), that have characteristic brightnesses, color, slopes, sizes, etc. Thus a texture can be regarded as a similarity grouping.”
- (Duraiswami) “Texture is something that repeats with variation”.
- Some Texture Measures:
  - Co-occurrence Matrix: Statistics Computed from Distribution of Gray Levels across the Image at Different Orientations
  - “Filter Banks”: Filtering Image with Various Linear Filters Corresponding to Multiple Patterns at Various Scales, e.g. Weighted of Gaussians at Different Scales
  - Gabor or Wavelets Filters, Steerable Pyramid (Simoncelli): Provide Local Spatial Frequency Analysis



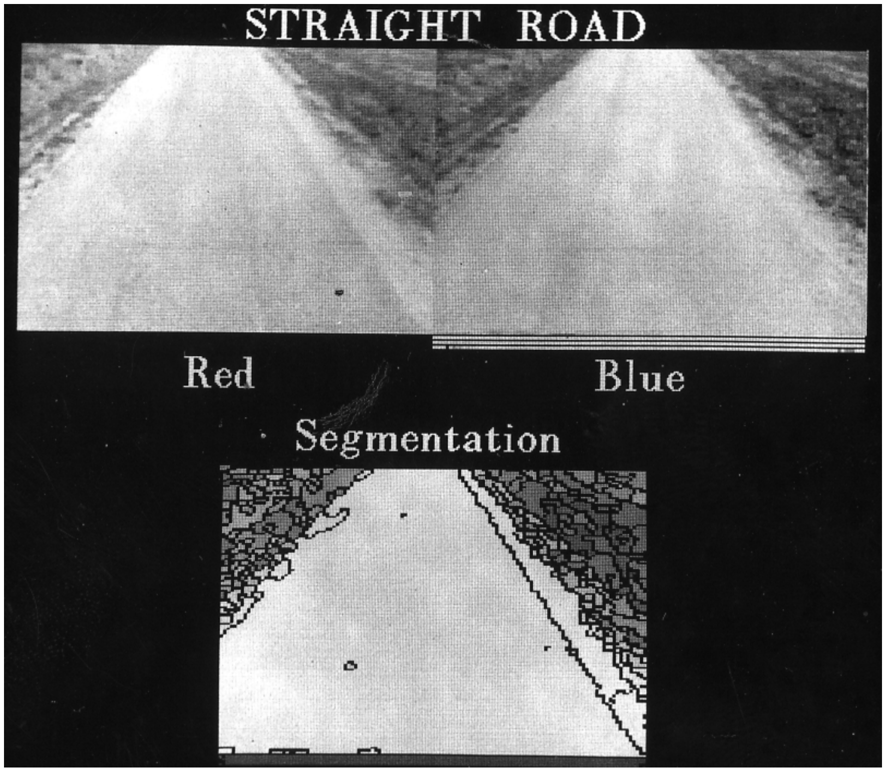
http://www.ux.uis.no/~tranden/brodatz.html

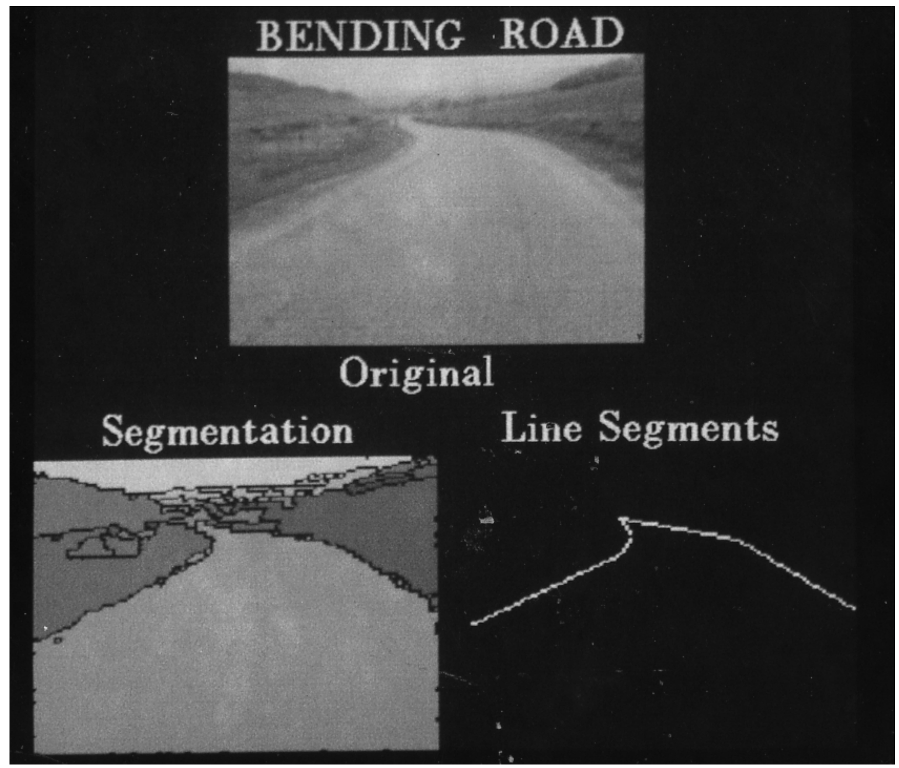
Region-Based Segmentation

- Iterative Region Growing
  - First Iteration: Each pixel represents an individual region
  - Next Iteration: Regions are merged if the criterion for merging is satisfied (e.g., the variance of the pixel intensities in the merged region is below a given threshold)
    - Merged regions can be adjacent or not
    - One or several merges can happen at each iteration
  - Iterate until no more possible merging or until stopping criterion is satisfied, e.g., a minimum number of regions has been reached.
  - Successive Iterations can be represented by a tree structure where {Root: Complete Image; Leaves: Individual Pixels; Branches: Relations between Regions and Subregions}
- Remarks:
  - Iterative Region Splitting
    - Reverse process starting with entire image as one region
  - Split and Merge
    - Iterative Succession of splitting and growing regions based on separate criteria for splitting and merging

Region-Based Segmentation

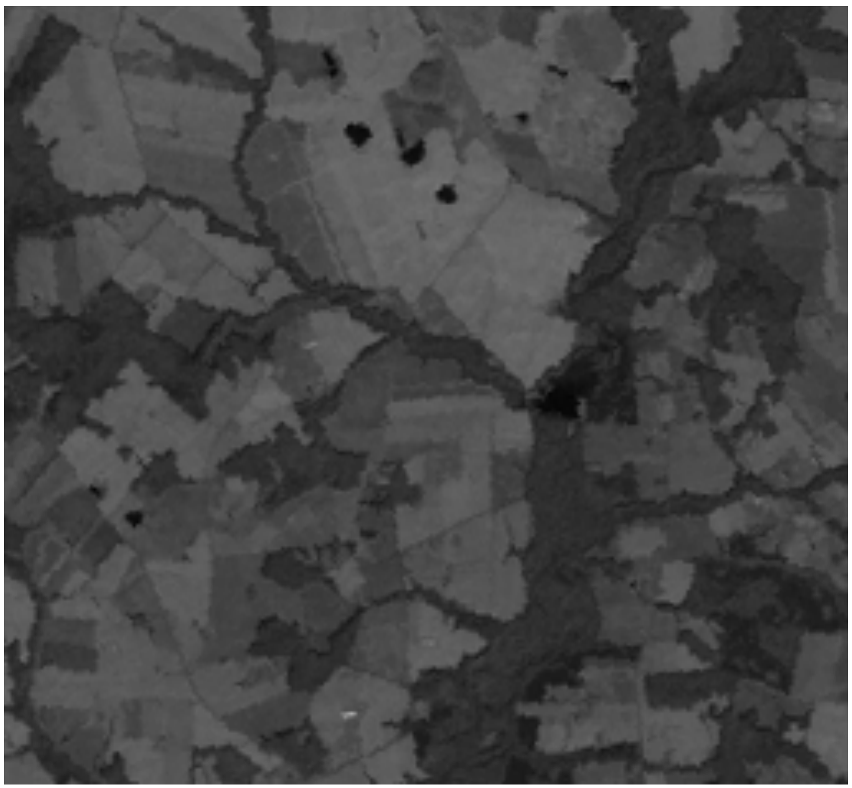
Road Following Results

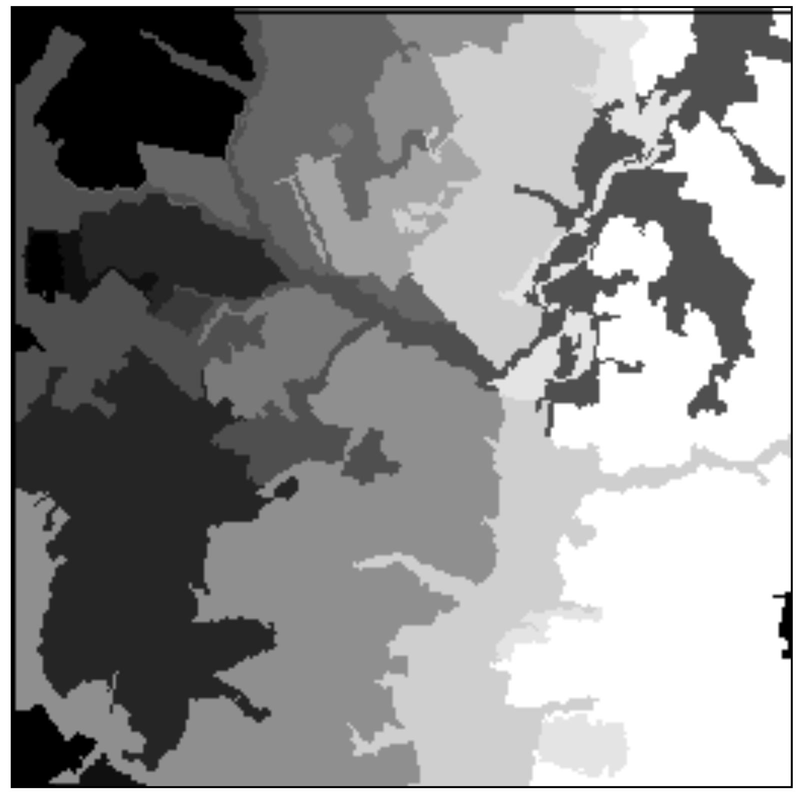




Region-Based Segmentation

Landsat Thematic Mapper Segmentation
(James Tilton/NASA GSFC)





Combining Regions and Edges

Landsat Thematic Mapper Segmentation

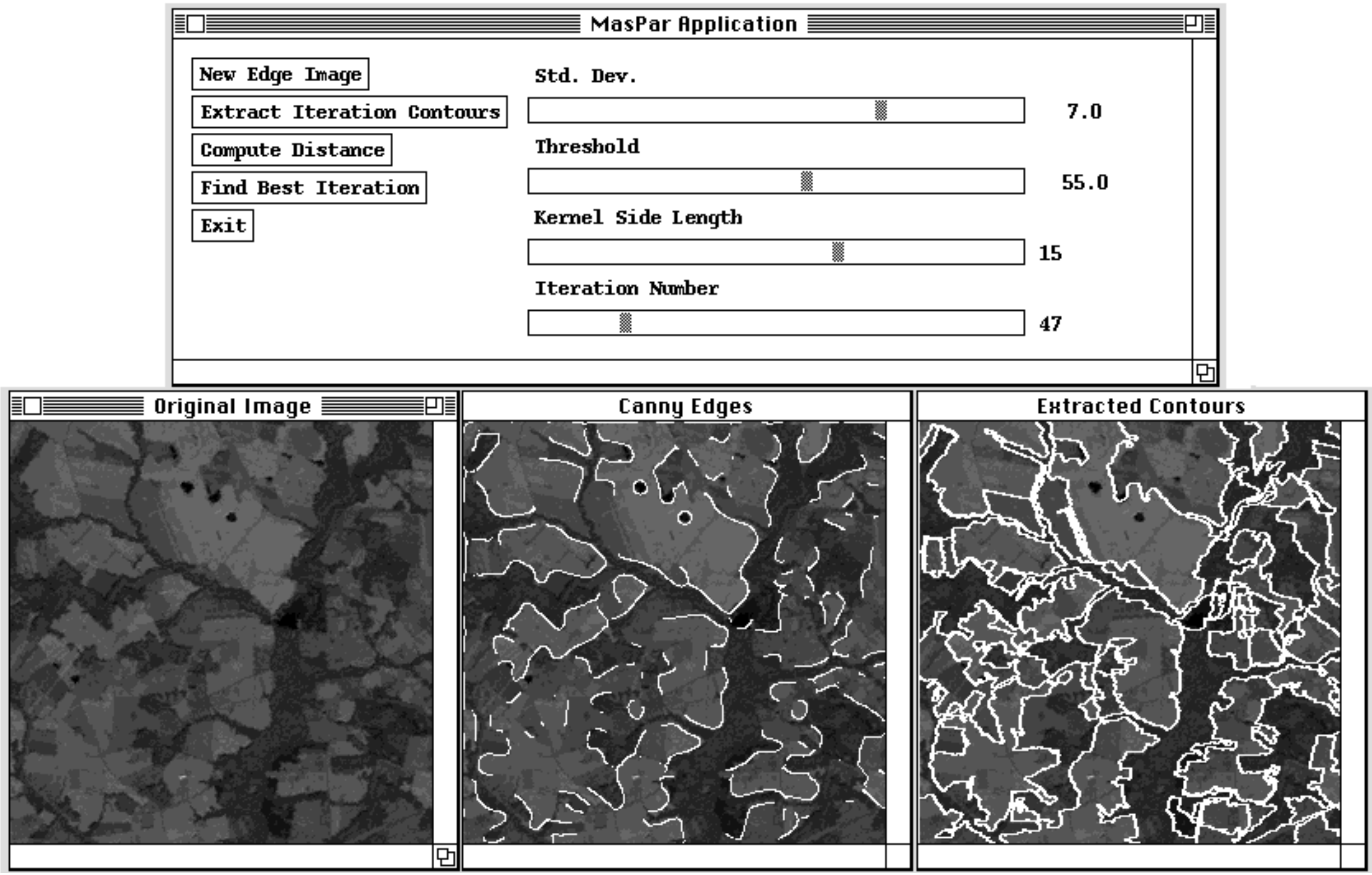


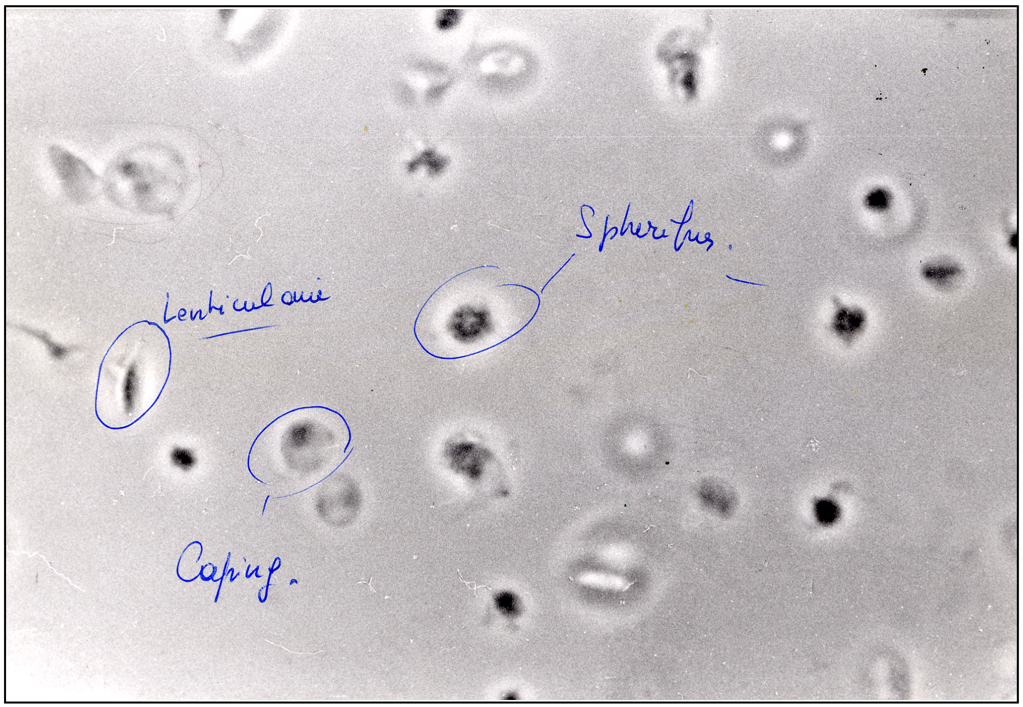
Image Modeling and Understanding

Understanding Images

- A-Priori Knowledge
  - Domain Knowledge
    - o Medical
      - Radiology or Cytology, … If Cytology: Blood Cells, Cancer Cells, …
    - o Remote Sensing
      - Space Science or Earth Science. If Earth Science: Agriculture, Change Detection (e.g., forest monitoring), Invasive Species, …
  - World Model or “Ground Truth”
- Based on “Low-Level and Intermediate-Level Processing”
    - o Pixel Classification, Image Features, Grouping of Image Features, …
- “High-Level Processing”: Image Understanding or Computer Vision/Artificial Intelligence Techniques
  - Decision Trees, Knowledge-Based Systems, Expert Systems, Intelligent Agents
      - o Object Recognition (e.g., Crater, Boulder, Rock Detection, …)
      - o Region Labeling (e.g., Trees, Water, Road, Buildings, …)
      - o 3D World Modeling (e.g., Pose Estimation for AR&D, …)

Blood Platelets Classification

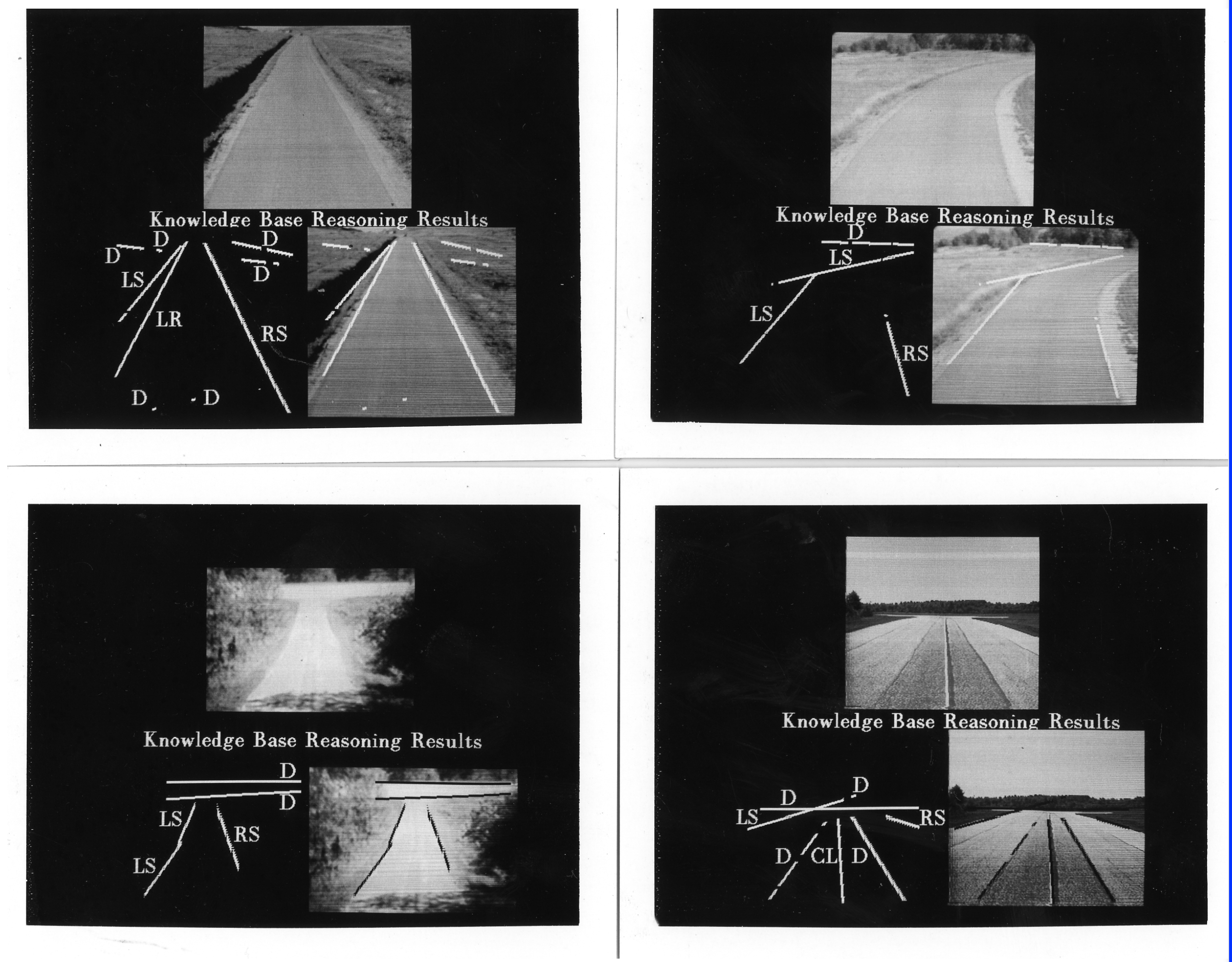
- A-Priori Knowledge
  - Blood Platelets Recognition after Freezing
  - Functional level related to Morphology and Texture
- Image Understanding
  - Classification into 7 Classes based on geometric shapes, geometric and texture measurements, “Lenticular”, “Lenticular with Pseudopods”, “Circular”, “Circular with Pseudopods”, “Capping”, “Aggregate”, “Artefact”



- Measurements:
  - Perimeter
  - Surface
  - Minimal Distance from Gravity Center to Contour
  - Maximal Distance from Gravity Center to Contour
  - Circularity Measure
  - Elongation Measures
- **Classification** by Decision Tree and Rule-Based System

Road Following

- A-Priori Knowledge
  - Road Networks
  - “Pencil of Lines” converging to a Vanishing Point
- Image Understanding
  - Classification of Lines into
    - “Left Road”
    - “Left Shoulder”
    - “Right Road”
    - “Right Shoulder”
    - “Center Road”
    - “Discarded”



Additional Reading

BOOKS:

- A. Rosenfeld and A.C. Kak, “Digital Image Processing,”Academic Press, 1982.
- D.A. Forsyth and J. Ponce, “Computer Vision: A Modern Approach,” Prentice Hall, 2003.
- R.O. Duda and P.E. Hart, “Pattern Classification and Scene Analysis,” John Wiley & Sons, 1973.
- B. Jähne, “Digital Image Processing: Concepts, Algorithms and Scientific Applications,” Springer-Verlag, 1991.
- T.M. Lillesand and R.W. Kiefer, “Remote Sensing and Image Interpretation,” John Wiley & Sons, Inc., 1987.
- J.G. Moik, “Digital Processing of Remotely Sensed Images,” NASA Technical Report SP-431, 1980.
- P.H. Swain and S.M. Davis, “Remote Sensing: The Quantitative Approach,” McGraw Hill, 1978.

ON LINE:

- http://www.umiacs.umd.edu/~ramani/cmsc426/index.html
- http://www.cs.cmu.edu/afs/cs/project/cil/ftp/html/vision.html
- http://www.dai.ed.ac.uk/CVonline/